

Aircraft Wake Vortices:

An Annotated Bibliography (1921–2020)

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DOT TSC (now DOT Volpe Center) Supporting FAA Flight Test at NAFEC, 1972
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14. ABSTRACT This is an updated version of the "Hallock, J. N., Aircraft Wake Vortices: An Annotated Bibliography (1923 - 1990), DOT-FAA-RD-90-30 / DOT-VNTSC-FAA-90-7, 1991" and other related historical bibliographies. This annotated bibliography consists of abstracts of publications on aircraft wake vortices and related fields. This material was developed as part of the Volpe Center support to the sponsoring agencies over time in order to facilitate the understanding of the open literature effort and is not an official nor comprehensive archive. In keeping with the historical term of "wake turbulence", jet-wash and jet-blast related references that have prominent historical significance are included. Selected references on leading edge vortices are also included if they have implication on either wake evolution or vortex breakdown behind the wing.					
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Foreword/Preface

The wake turbulence bibliography effort traces back to the printed version of "Hallock, J. N., Aircraft Wake Vortices: An Annotated Bibliography (1923 - 1990), DOT-FAA-RD-90-30, 1991". The subsequent enlargement of the material was maintained online on a DOT Volpe Center website until 2020 where a combination of technical and personnel constraints halted the continuation of the effort. It was decided by the FAA Wake Turbulence Research and Development Office (i.e., the sponsor of the wake work at the time of this writing) that although the material is no longer accessible online, it is still of value to make the material up to 2020 available to the wake turbulence community – hence the current electronic publication of the updated Annotated Bibliography. This updated electronic bibliography replaces the earlier printed versions of "Aircraft Wake Vortices: An Annotated Bibliography (1923 - 1990), DOT-FAA-RD-90-30, 1991", "A Summary of Helicopter Vorticity and Wake Turbulence Publications With an Annotated Bibliography, J. J. Shrager, FAA-RD-74-48, 1974", and "Rotorcraft Wakes - An Annotated Bibliography, J. N. Hallock, FA-427-PM-84, 1986". The bibliography consists of abstracts of publications on aircraft wake vortices. This material was developed as part of the Volpe Center support to the sponsoring agencies over time in order to facilitate the understanding of the open literature effort and is not an official nor comprehensive archive.

Like many modern ideas, one of the earliest known references to wake vortices appeared in the notes of Leonardo da Vinci. After the great Leonardo, little was published until Lord Rayleigh described his "vortexes." However, modern aircraft wake vortex history in terms of scientific understanding began with the futile attempts by Lanchester to publish his work in a journal. Fortunately, the material eventually appeared in his book *Aerodynamics*; one of his figures is still used today. Operationally, aircraft wake vortices became a very practical consideration in the 1970s when wide body jets started to be in service, although flight testing on wake vortices appears to trace back to the early 1950s.

To make the task of compiling a bibliography a finite one, certain material was not included. To be considered for this document the publication had to possess a possible implication in the setting of separation standards in the Air Traffic Control System. The bibliography includes theoretical, computational, and experimental work which describes the nature of a vortex (its growth, decay, structure, formation, interaction with the environment, etc.), the effects of vortices on other aircraft, the various means to avoid or to alleviate the severity of a vortex encounter, and technologies that directly contributed to the understanding of the state-of-the-art vortex knowledge. In keeping with the historical term of "wake turbulence", jet-wash and jet-blast related references that have prominent historical significance are included, particularly because operationally wake turbulence separations are often applied to jet-blast in the absence of other guidance. Leading edge or delta wing vortices are considered, but only those that contain relevant information on decays, breakdown and initial circulation estimates are included.

The references are given in the form used by the American Institute of Aeronautics and Astronautics (AIAA). Since material often appeared in more than one publication (such as first in an AIAA paper, then in one of their archival journals), the more accessible source (usually the refereed journal article) was used in this report.

Special thanks to the current and past sponsors that led to the compilation of this material. They include Jillian Cheng, Jeffrey Tittsworth, Paul Strande, Steven Lang and George Greene of the FAA, as well as Wayne Bryant and Edward Johnson of NASA. We also acknowledge the countless contributors over the years that augmented and contributed to the content via correspondence. This compilation is completed under the FAA-Volpe Center Interagency Agreement: A2503-069-069-075840, Order: O2503-069-069-091203.

Abbiss, J. B., Sharpe, P. R. and Wright, M. P.

"EXPERIMENTS USING A THREE-COMPONENT LASER-ANEMOMETRY SYSTEM ON A SUBSONIC FLOW WITH VORTICITY"

RAE T R-8008, June 1980, Royal Aircraft Establishment, Farnborough, England.

Experiments with a three-component laser anemometer on the wake and vortex structure behind a model wing at incidence in a 4ft x 3ft subsonic test section are described. Three colors from the output spectrum of an argon-ion laser were used for the three Doppler-difference arrangements. The complete optical system operated in backscatter and was mounted on a single table which could be translated in three orthogonal directions. An integrated data acquisition and reduction system was used incorporating a photon correlator and a Honeywell 6/36 minicomputer. The output data consisted of mean-velocity and turbulence-intensity values for all three components at each measurement point. From these data, the mean-velocity components in the directions of the conventional tunnel axes could be derived by means of a linear transformation. However, the measured turbulence intensities do not yield the turbulence intensities for these components without additional assumptions or supplementary information.

Abbott, T. S.

"COCKPIT-DISPLAY CONCEPT FOR EXECUTING A MULTIPLE GLIDE-SLOPE APPROACH FOR WAKE-VORTEX AVOIDANCE"

NASA TP-2386, February 1984, NASA Langley Research Center, Hampton, VA.

A piloted simulation study was undertaken to determine the feasibility of utilizing a forward-looking display to provide information that would enable aircraft to reduce their in-trail separation interval, and hence increase airport capacity, through the application of multiple glide-path approach techniques. The primary objective of this study was to determine whether information could be satisfactorily provided on a head-up display (HUD) format to permit the pilot to conduct a multiple glide-slope approach while maintaining a prespecified in-trail separation interval. The tests were conducted in a motion-base cockpit simulator configured as a current-generation transport aircraft and included dynamic effects of the vortices generated by the lead aircraft. The information provided on the HUD included typical aircraft guidance information and the current and past positions of the lead aircraft. Additionally, the displayed information provided self-separation cues that allowed the pilot to maintain separation on the lead aircraft. Performance data and pilot subjective ratings and comments were obtained during the tests. The results of this study indicated that multiple glide-slope approaches, procedurally designed for vortex avoidance, are possible while maintaining pilot work load and performance within operationally acceptable limits. In general, it would seem that multiple glide-slope approaches are possible even under reduced in-trail separation conditions if the pilot is provided with adequate situational information.

Abbott, T. S.

"SIMULATION OF A COCKPIT-DISPLAY CONCEPT FOR EXECUTING A WAKE-VORTEX AVOIDANCE PROCEDURE"

NASA TP-2300, April 1984, NASA Langley Research Center, Hampton, VA.

A piloted simulation study has been undertaken to determine the feasibility and potential benefits of utilizing a forward-looking display to provide information that would enable aircraft to reduce their in-trail separation, and hence increase runway capacity, through the application of multiple glide-path approach techniques. This portion of the study was an initial exploration into a concept in which traffic information was added to a head-up display (HUD) format to allow the pilot to monitor the traffic situation and to self-space on a lead aircraft during a single glide-path approach task. The tests were conducted in a motion-base cockpit simulator configured as a current-generation transport aircraft and include the dynamic effects of the vortices generated by the lead aircraft. The information provided on the HUD included typical aircraft guidance information and the current and past positions of the lead aircraft. Additionally, the displayed information provided self-separation cues which allowed the pilot to maintain separation on the lead aircraft. The results of this study indicate that the display concept could provide sufficient information to the pilot for traffic monitoring and self-separation.

Abdelazim, S., Santoro, D., Arend, M., Moshary, F. and Ahmed, S.

"WIND VELOCITY ESTIMATE AND SIGNAL TO NOISE RATIO ANALYSIS OF AN ALL FIBER COHERENT DOPPLER LIDAR SYSTEM"

16th Coherent Laser Conference, June 2011, Long Beach, CA.

In CDL, a laser pulse is transmitted into the atmosphere and the Doppler shifted signal that scatters off atmospheric aerosol particles is detected by beating this signal with a local oscillator (LO). The resulting RF signal has a Doppler shift proportional to the speed of aerosol particles along the line of sight of the laser beam. In this paper, we present preliminary results from our all fiber 1.5-micron CDL. The range dependence of the theoretical wideband SNR of an atmospheric backscattered signal is compared to experimental results using a 6-inch diameter refractive telescope. The system performance is dependent on optimizing the LO power and our previous research presented a detailed analysis of an optimum LO power and its effect on detector's efficiency.

Abdelazim, S., Santoro, D., Arend, M., Moshary, F. and Ahmed, S.

"ALL-FIBER COHERENT DOPPLER LIDAR FOR WIND SENSING"

15th Coherent Laser Radar Conference Proceedings, June 2009, Toulouse, France, pp. 283-286.

Coherent Doppler LIDAR is being utilized to develop a mobile wind speed measuring station. We are building an all fiber-based eye safe laser system to measure wind speed in urban areas. A 1.5-micron polarization maintained fiber optics master oscillator power amplifier system is used which leverages components from the telecommunication industry. We chose a heterodyne balanced detection to suppress the RIN noise. We have calculated the optimum local oscillator power for maximum optical

detector's efficiency. A/D conversion will be performed at 400 MHz by using a data acquisition card with FPGA on board, which can be programmed to perform autocorrelation and/or FFT onboard for faster performance. This system can be used along with other units on top of high buildings in New York City as a way of detecting wind speed profile for Homeland security.

Abdel-Kareem, W.

"TRACKING OF VORTICAL STRUCTURES IN THREE-DIMENSIONAL DECAYING HOMOGENEOUS ISOTROPIC TURBULENCE"

International Journal of Modern Physics C, Vol. 22, Issue 12, 2011, pp. 1373-1391.

Direct numerical simulation of three-dimensional decaying homogeneous isotropic turbulence with a resolution of 128 cubed is carried out using the Lattice Boltzmann Method (LBM). The aim of this paper is to investigate the statistical characteristics of the obtained turbulent flow field and the behavior of the vortical structures. Most of the LBM simulations of decaying turbulence were mainly focused on the statistical results of the velocity field, however the characteristics of the coherent vortices and their time evolution are ignored. In this paper, the statistical properties of the velocity field as well as the extraction and tracking processes of individual vortices are considered. Results show that the present simulation could recover important features of turbulence such as isotropy, skewness, energy spectrum and elongated vortical structures. A vortex ring is identified in the flow field which can be considered as a sign for the existence of vortex rings in homogeneous isotropic turbulence. Forward and reverse tracking of individual vortical structures shows that vortex rings can be generated from the interaction and the overlapping of vortex tubes.

Abdullah, A. J.

"THE 'MUSICAL' SOUND EMITTED BY A TORNADO"

Monthly Weather Review, Vol. 94, No. 4, April 1966, pp. 213-220

This paper attempts to explain the 'whining' or 'hissing' sound reported from tornadoes. The leading hypothesis is that the air masses involved in the tornado circulation execute some free vibrations. It is found that these vibrations may be in the audible range for a small vortex whose radius is of the order of 10 m. or less. A formula is obtained which relates the frequency of the tone to the inner radius of the vortex. This formula is amenable to experimental verification.

Abello, J. C. and George, A. R.

"WAKE DISPLACEMENT MODIFICATIONS TO REDUCE ROTORCRAFT BLADE -- VORTEX INTERACTION NOISE"

Journal of Aircraft, Vol. 41, No. 2, March-April 2004, pp. 290-303

Increasing the vertical separation between the rotor and its wake can reduce the strength of blade-vortex interaction (BVI) noise. A simple, first-order analytical model is developed to estimate the vertical distance between the rotor and the wake at any location of interest in the rotor disk. This model is used as an indicator to evaluate the potential effects of added forces, descent angle, advance ratio, and thrust coefficient on the separation between the wake and the rotor with the aim of identifying strategies that maximize this distance at a particular rotor disk location. The analysis focuses on landing approaches for helicopters and tiltrotors operating near helicopter configuration. The most appropriate strategies to increase this separation at the location of interest are found to depend on whether the wake is initially above or below the rotor. Added drag, added downforce, shallower descents, lower advance ratios, and higher thrust coefficients are shown to be desirable if the wake is initially below the rotor plane at the location of interest; this is the case of tiltrotor approaches and some helicopter descent operations. On the other hand, added thrust, added lift, steeper descents, higher advance ratios, and lower thrust coefficients are usually more appropriate if the wake is initially above the rotor plane at the location of interest; this is the case for other helicopter descent operations.

Abernathy, F. H. and Kronauer, R. E.

"THE FORMATION OF VORTEX STREETS"

Journal of Fluid Mechanics, Vol. 13, Issue 1, May 1962, pp. 1-20.

The formation of vortex streets in the wake of two-dimensional bluff bodies can be explained by considering the non-linear interaction of two infinite vortex sheets, initially a fixed distance, h , apart, in an inviscid incompressible fluid. The interaction of such sheets (represented in the calculation by rows of point-vortices) is examined in detail for various ratios of h to the wavelength, a , of the initial disturbance. The number and strength of the concentrated regions of vorticity formed in the interaction depend very strongly on h/a . The non-linear interaction of the two vortex sheets explains both the cancellation of vorticity and vortex-sheet broadening observed in the wakes of bluff bodies.

Abernathy, F. H. and Menkes, J.

"AN ESTIMATE OF THE POWER REQUIRED TO ELIMINATE TRAILING VORTICES BY SUCTION"

IEEE Proceedings, Vol. 58, No. 3, March 1970, pp. 326-327.

The feasibility of reducing the hazards of trailing vortices on closely spaced parallel runways is examined. The proposed solution involves the application of suction along the runways. A simplified computer simulation indicated that the application is feasible and that the required horsepower is modest.

Abernathy, F. H., Menkes, J. and Uberoi, M. S.

"AN ESTIMATE OF THE POWER REQUIRED TO ELIMINATE TRAILING VORTICES BY SUCTION"

DOT-1081, Report of Dept. of Transportation Air Traffic Advisory Committee, Vol. 2, Appendix B-4, December 1969, pp. 55-77.

The fullest utilization under IFR conditions of closely spaced parallel runways might very well depend ultimately on our ability to eliminate or at least to control the hazards of wake turbulence. Two parameters determine the severity of the problem: crosswind and aircraft weight. Of all the possible solutions, one of the least promising is to attempt to change the character of the vortex as it leaves the wing. A better approach is to affect the trajectory of the trailing vortices by suction. This solution has the attractive feature that the vortex motion is influenced without relying on viscous dissipating mechanisms. The conceptual scheme involves placing one or more ditches between the runways, covered with a heavy grating, which house the suction blowers.

Abid, M.

"NONLINEAR MODE SELECTION IN A MODEL OF TRAILING LINE VORTICES"

J. Fluid Mech., Vol. 605, 2008, pp. 19-45

Nonlinear mode selection, from initial random Gaussian field perturbations, in a model of trailing line vortices (swirling jets), in the breakdown regime, is addressed by direct numerical simulations with a Reynolds number equal to 1000. A new concept of mode activity in the nonlinear evolution is introduced. The selected modes, according to their activities, are reported and related to strain eigenvectors (with maximum eigenvalues) of the basic flow corresponding to the trailing line vortex under consideration. The selected modes are also related to results from the linear eigenmode (exponential growth) instability theory using the concept of dispersion relation envelope. It is found that the global mode hypothesis of the linear eigenmode theory is violated near the flow axis when the swirl number increases. However, far from the flow axis the linear eigenmode theory is in good agreement with the nonlinear evolution in the breakdown regime. The discrepancy between the nonlinear evolution and the linear eigenmode theory is related to the transient growth of optimal perturbations resulting from the non-normality of the linearized Navier-Stokes equations about shear flows. A clear distinction between an eigenmode, an optimal perturbation (non-modal) and a direct numerical simulation (DNS) mode is made. It is shown that the algebraic (transient) growth contributions from the inviscid continuous spectrum could trigger nonlinearities near the flow axis.

Abid, M. and Brachet, M. E.

"DIRECT NUMERICAL SIMULATIONS OF THE BATCHELOR TRAILING VORTEX BY A SPECTRAL METHOD"

Physics of Fluids, Vol. 10, No. 2, February 1998, pp. 469-475

The nonlinear vorticity dynamics of the Batchelor trailing vortex is presented. Direct numerical simulations of the three-dimensional, incompressible, Navier-Stokes equations by a spectral method are used. It is shown that the initial vortex core is subjected to three transformations: a twisting phase, a lateral expansion of its cross section and formation of a spiral structure. These transformations are accompanied by a gradual deceleration of axial velocity. Mean kinetic energy is

then transferred to radial velocity. When the transfer is maximum a secondary instability is initiated leading to the spiral structure. These transformations agree with vortex breakdown observed in recent experiments.

Abid, M., Andreotti, B., Douady, S. and Nore, C.

"OSCILLATING STRUCTURES IN A STRETCHED-COMPRESSED VORTEX"

J. Fluid Mech., Vol. 450, 2002, pp. 207-233

The dynamics of a vortex subject to a localized stretching is numerically investigated. The structure of the flow is analyzed in the case of an initially two-dimensional vortex surrounded by a periodic array of vortex rings localized far from its core. Amplified oscillations of both the axial vorticity and the stretching are found, in strong contrast with Burgers-like vortices. The resulting dynamics is the appearance, around the vortex, of successive vortical structures of smaller and smaller radius and alternate sign embedded in the previous vortical rings. The frequency scaling of the oscillations is recovered by linear analysis (Kelvin modes) but not the amplification nor the shape of the successive tori. An inviscid model based on structures is presented, which compares better with the numerical computations. These results suggest that the formalism of Kelvin waves is not sufficient to describe the full dynamics, which is instead related to the feedback of rotation on stretching and more conveniently described in terms of localized structures. We finally discuss the relative timescales of vortex stretching and of vortex reaction. The Burgers-like vortices, where there is no such reaction, turn out to correspond to a nearly pure strain field, slightly disturbed by rotation.

Abid, R. and Schmitt, R.

"EXPERIMENTAL STUDY OF A TURBULENT HORSESHOE VORTEX USING A THREE-COMPONENT LASER VELOCIMETER"

AIAA Paper No. 1986-1069, Atlanta, GA, May 1986

The turbulent horseshoe vortex flow generated by a simplified wing-body junction has been experimentally studied. Oil surface flow visualization, static wall pressure measurements, and flow field measurements were made in the separated region upstream of the obstruction leading edge. Mean flow measurements on the plane of symmetry indicate that the three-dimensional separation was confined to a region near the plate. The region of reversed flow was approximately a fifth of the boundary layer thickness. The theoretical streamline pattern suggested by oil surface flow visualization is confirmed.

Aboelkassem, Y.

"BLADE VORTEX INTERACTIONS: EXPERIMENTAL MEASUREMENTS OF THE NEAR-FLOW FIELD"

Journal of Fluid Science and Technology, Vol. 4, No. 1, 2009, pp. 138-155.

The near-field flow structure of an intense streamwise vortex filament encountering normally with a blade tip vortex was investigated experimentally. Three cases were investigated, direct impingement, interactions on the pressure side and interactions over the suction side. The effects of blade-vortex interaction were found to be strongly dependent on whether the vortex filament passed over the pressure or suction side of the blade. In case of zero vortex-blade tip separation (direct impingement), the peak tangential velocity and total circulation of the interaction vortex remained basically unchanged, regardless of downstream distance, but had values larger than the generator vortex, while the core circulation and the core radius increased almost linearly with downstream distance, like an undisturbed generator vortex. The maximum total turbulent energy decreased as x/c increased. In summary, the present experiment deals with the normal interactions of streamwise vortex with another tip vortex shed by a blade end-tip, and focuses on the resultant vortex structures and peak values due to the interaction itself.

Aboelkassem, Y.

"TRAILING VORTEX FILAMENT: A NOVEL SIMILARITY ANALYSIS"

Journal of Aircraft, Vol. 44, No. 2, March-April 2007, pp. 683-687

The classical spatial-decay analysis of a trailing vortex's line filament is extended to include the temporal effects. Based on the order of magnitude argument, the time-dependent governing equations are reduced into a simpler form. New similarity variables are introduced and have been used to transform the time-dependent partial differential equations into an ordinary set. The latter have proven to be identical to the steady analysis given previously by Newman. Consequently, the solution to the time-decay problem is found by analogy to the steady-state subset and without having formally to solve the governing equations. In other words, the time-decay problem is similar to the axial decay one. In addition, the present theoretical study shows the space-time analogy shared by a group of self-similar structure vortices. The steady vortices can be transformed into time decaying and vice versa. This transformation depends solely on the similarity variable. The present results are confirmed by available experimental measurements and have shown that steady and decaying vortices, irrespective of their size, strength, and time level, should collapse into a single curve, that is, the space-time self-similarity hypothesis is indeed validated.

Aboelkassem, Y. and Vatisstas, G. H.

"NEW MODEL FOR COMPRESSIBLE VORTICES"

Journal of Fluids Engineering, Vol. 129, August 2007, pp. 1073-1079

A new analytical solution for self-similar compressible vortices is derived in this paper. Based on the previous incompressible formulation of intense vortices, we derived a theoretical model that includes density and temperature variations. The governing equations are simplified assuming strong vortex conditions. Part of the hydrodynamic problem (mass and momentum) is shown to be analogous to the incompressible kind and as such the velocity is obtained through a straightforward variable

transformation. Since all the velocity components are bounded in the radial direction, the density and pressure are then determined by standard numerical integration without the usual stringent simplification for the radial velocity. While compressibility is shown not to affect the tangential velocity, it influences only the meridional flow (radial and axial velocities). The temperature, pressure, and density are found to decrease along the converging flow direction. The traditional homentropic flow hypothesis, often employed in vortex stability and optical studies, is shown to undervalue the density and greatly overestimate the temperature. Comparable to vorticity diffusion balance for the incompressible case, the incoming flow carries the required energy to offset the contributions of conduction, viscous dissipation, and material expansion, thus keeping the temperature steady. This model is general and can be used to obtain a compressible version for all classical previous incompressible analysis from the literature such as Rankine, Burgers, Taylor and Sullivan vortices.

Aboelkassem, Y., Vatistas, G. H. and Esmail, N.

"VISCOUS DISSIPATION OF RANKINE VORTEX PROFILE IN ZERO MERIDIONAL FLOW"

Acta Mech Sinica, Vol. 21, 2005, pp. 550-556

An analytical solution is given for a time-delay Rankine vortex profile due to viscous effects. The vortex filament is assumed to be isolated, strong, concentrated and having zero-meridional flow (i.e. radial and axial velocities are equal to zero). Zero-meridional renders the governing equations for an unsteady, incompressible and axisymmetric vortex in a simple form. Based on the tangential momentum equation, the spatial-temporal distributions of the swirl velocity are given in terms of Fourier-Bessel series by using separation of variables technique. A general formula is derived by total differentiation of the swirl velocity with respect to time, depicting the viscous dissipation for Oseen and Taylor-like vortex profiles. This analysis is validated by comparison with previous experimental data.

Abramson, S. and Burnham, D. C.

"WIND DATA FROM KENNEDY AIRPORT"

DOT/FAA/ND-97-3, May 1997, DOT Volpe Center, Cambridge, MA.

A 700-foot array of horizontal and vertical single axis anemometers was installed at New York's Kennedy Airport on 30-foot poles under the approach to Runway 31R. One minute average measurements were recorded continuously, with a few breaks, from September 1994 through June 1995. Although the original purpose for the anemometers was to track the lateral position of wake vortices, the measurements also provide a database of wind and turbulence that can be used for other purposes. For example, the crosswind data has been used to evaluate four adaptive wake vortex separation systems based on the measured crosswind. This report documents the data formats and database characteristics and provides information on how to obtain a copy of the data.

Abramson, S. and Burnham, D. C.

"GROUND-BASED ANEMOMETER MEASUREMENTS OF WAKE VORTICES FROM LANDING AIRCRAFT AT AIRPORTS"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 13-1 to 13-7

In 1994 an array of two-axis propeller anemometers was installed at 10-meter height under the approach to Runway 31R at Kennedy Airport. Since the aircraft are typically 50 meters above the ground at the test location, the wake vortices rapidly descend toward the ground where they are readily detected and measured by the anemometers. In 1995 a similar installation was made on Runway 27 at the Memphis Airport. The ultimate goal of this study is to better understand when wake vortices remain in the flight path of following aircraft. The data collection system operates automatically and hence provides wake vortex data under all weather conditions and at all times of day and night with minimal cost. Real-time remote display of the vortex locations was implemented. The anemometers are augmented with additional weather sensors to provide meteorological data with greater detail than the standard surface weather observations. New processing methods for the anemometer data were developed to determine vortex height and strength in addition to the lateral position that was traditionally obtained from ground-based anemometers. The anemometer array is particularly appropriate for studying the interaction of wake vortices with the ground. It readily detects the secondary vortices detached from the boundary layer by the influence of the primary wake vortices; these secondary vortices produce the well known vortex bouncing. Such secondary vortices have not been seen by any other sensing system.

Abras, J. N., Narducci, R. and Hariharan N.

"WAKE BREAKDOWN OF HIGH-FIDELITY SIMULATIONS OF A ROTOR IN HOVER"

AIAA Paper 2019-0593, January 2019, San Diego, CA.

Complete wake breakdown is a well-documented phenomenon associated with computational fluid dynamic hover predictions. As the computational state-of-the-art for hover predictions has progressed, allowing for higher resolution of the rotor wake, this phenomenon has become more severe; thus, resolving this open question has become more important to increase understanding of how and why it occurs and define a path forward. The present work investigates the wake breakdown phenomena using the S-76 isolated rotor. This investigation includes a discussion of physical flow features that are felt to influence both physical and computational wake breakdown as well as an analysis of the computational inputs that can influence these flow features. This includes an analysis of relative vortex core position and strength as a function of wake breakdown and a parameter study to look at off-body grid structure. The grid study employs both cylindrical and Cartesian grids and different grid densities to investigate how these settings influence physical flow features and the initiation of wake breakdown. Rotating and stationary grids are also included in this study. As a result of these studies clear impacts to the wake breakdown have been discovered.

Abuharaz, M. and Ash, R. L.

"A NEW APPROACH FOR MODELING THE UNSTEADY BEHAVIOR OF TRAILING LINE AXIAL VORTICES"

AIAA Paper 2013-3188, June 2013, San Diego, CA.

A state variable procedure has been developed that can be used to study the influence of non-equilibrium pressure gradient forces on the stability of axial trailing-line vortices. In addition to previously-developed modified Navier-Stokes equations, a Poisson equation governing perturbation pressure fluctuations was developed that is of the same differential order as the velocity perturbation equations. A normal mode analysis was utilized to formulate the small perturbations in the vortical flow with radially-varying amplitudes, producing a system of ordinary differential equations governing the evolution of the normal modes in the flow. This has resulted in a more-consistent approach for analyzing the stability and unsteady behavior of these axial vortices.

Accardo, L., Cenedese, A. and Cioffi, F.

"EXPERIMENTAL ANALYSIS OF TIP VORTEX BY LASER DOPPLER ANEMOMETRY"

Proceedings of the International Symposium on Applications of Laser Anemometry to Fluid Mechanics, 1984, July 2-5, Lisbon

The aerodynamic performances of aircraft wings, helicopter rotors, marine propellers, and turbomachines are related to the presence of turbulent boundary layers and vortex sheet formation. The mutual interaction between boundary layer makes three-dimensional the phenomenon. This aspect is particularly evident at the wing/body junction and at the extremity of the wings or blades where tip vortices are formed. By means of laser Doppler anemometry, the velocity field is experimentally analyzed close to the tip in the near wake generated by a symmetrical wing with a rectangular plant. The analysis of experimental results shows that there exists a strong axial current in the core of the tip vortex. A velocity logarithmic trend is formed in the zone where there is interaction between the irrotational flow and the core vortex.

Ackroyd, J. A. D.

"THE SPITFIRE WING PLANFORM: A SUGGESTION"

Journal of Aeronautical History, Paper No. 2013/02, 2013, London, U.K.

The paper concerns the aerodynamic design of the Spitfire wing and the involvement of the Canadian-born Beverley Shenstone in this. It is suggested that the wing's distinctive double-ellipse planform could have come from Prandtl's work at Gottingen on finite wing theory.

Acosta, R., Hughes, I. and Petersen, R.

"VISUALIZATION OF WAKE VORTEX EFFECTS ON AIRCRAFT"

B.S. Thesis, June 1998, Hogeschool van Amsterdam, Amsterdam, The Netherlands.

The assignment issued by Dr. J. N. Hallock, manager of the Aviation Safety Division of the Volpe National Transportation Systems Center in Cambridge, Massachusetts, is to visually record aircraft landings at Runway 31R at JFK International Airport. The position and the motion of the aircraft must be retrieved from the recorded images. The data of the motion of all aircraft will be analyzed along with the vortex data gathered by the Volpe Center in order to determine if any aircraft motion is related to wake vortices caused by preceding landing aircraft. After a theoretical analysis a method for recording was chosen involving the use of two cameras. This method is called stereoscopic imaging. The application of stereoscopic imaging as developed does not require input from other systems for its functioning. The accuracy is reliable if the system is calibrated correctly and aligned and stays aligned correctly during recording. The equipment and tools for the system are relatively inexpensive in comparison to having a person analyze recordings of a single imaging system. Of the two test periods that were spent at the JFK test site there were no valuable recordings taken. During the last test period the calibration for both cameras were achieved as well as a measurement of a still object. The error in the measurement proved to be small. The system that is developed and described completely within the contents of this thesis must be set up correctly for it to function adequately. Time as well as money need to be invested into equipment for aligning the cameras correctly to use this system for gaining accurate data, which can then be analyzed in combination with wake vortex data to prove what effect wake vortices have on aircraft.

Adam, I. G.

"VORTEX WAKE AND EXHAUST PLUME INTERACTION, INCLUDING GROUND EFFECT"

Ph.D. Thesis, 1998, Old Dominion University, Norfolk, VA

Computational modeling and studies of the near-field wake-vortex turbulent flows, far-field turbulent wake-vortex/exhaust-plume interaction for subsonic and High-Speed Civil Transport (HSCT) airplane, and wake-vortex/exhaust-plume interaction with the ground are carried out. The three-dimensional, compressible Reynolds-Averaged Navier Stokes (RANS) equations are solved using the implicit, upwind, Roe-flux-differencing, finite-volume, scheme. The turbulence models of Baldwin and Lomax, one-equation model of Spalart and Allmaras and two-equation shear stress transport model of Menter are implemented with the RANS solver for turbulent-flow modeling. For the near-field study, computations are carried out on a fine grid for a rectangular wing with a NACA-0012 airfoil section and a rounded tip. The focus of study is the tip-vortex development, the near-wake-vortex roll-up, and validation of the results with the available experimental data. For the far-field study, the computations of wake-vortex interaction with the exhaust-plume of a single engine of a medium-size subsonic aircraft in a holding condition and two engines of a HSCT in a cruise condition are carried out using an overlapping zonal method for several miles downstream. The overlapping zonal method has been carefully developed and investigated for accurate and efficient calculations of the far-field wake-vortex flow. The results of the subsonic flow are compared with those of a Parabolized Navier Stokes (PNS) solver known as the UNIWAKE code. Next, the problem of wake-vortex/ground interaction is investigated. For the simulation of this problem, typical velocity profiles of a tip vortex with and without the exhaust-plume temperature profiles are used for inflow boundary conditions and the computations are carried out

using the overlapping zonal method for long distances downstream. The effects of the exhaust-plume temperature on the vortex descent, ground boundary-layer separation, vortex rebound and vortex decay are studied and validated with the available experimental data. A parametric study, which covers the effects of atmospheric conditions such as axial wind, crosswind, wind shear, turbulence, and Reynolds number on vortex motion and dynamics near the ground, is also carried out.

Adam, I. G. and Kandil, O. A.

"INVESTIGATION OF THREE-DIMENSIONAL VORTEX-WAKE INTERACTION WITH THE GROUND"

AIAA Paper No. 1998-0594, Reno, NV, January 1998

Three-dimensional, computational study of vortex-wake flow, with and without exhaust plume, near the ground is carried out. The Navier-Stokes (NS) equations are solved using the implicit, upwind, Roe flux-differencing, finite volume scheme. The computations of vortex-wake interaction with the ground are carried out using overlapping zonal method for long distances downstream. Typical velocity profiles of a tip vortex with and without exhaust plume temperature profiles are used for inflow boundary conditions. The effects of the plume temperature on the vortex descent, boundary-layer separation and vortex rebound are studied and validated with the available experimental data. Moreover, the effect of the flow in the axial direction on the vortex descent is studied by using two different axial velocity profiles at the inlet boundaries.

Adams, G. N. and Gilmore, D.C.

"SOME OBSERVATIONS OF VORTEX CORE STRUCTURE"

Canadian Aeronautics and Space Journal, Vol. 18, June 1972, pp. 159-162.

During observation of propeller tip vortex locations by means of smoke and stroboscopic lighting, a fortuitous atmospheric condition resulted in the formation of visible condensation in the vortex cores. The core structure was seen to be extremely complex, with evidence of concentric cells of axial flow, bounded by families of ring vortices. Photographs were taken, and a selection of these is presented here, for the inspiration of fluid dynamicists and the edification of others.

Adamson, D. and Boatright, W. B.

"INVESTIGATION OF DOWNWASH, SIDEWASH, AND MACH NUMBER DISTRIBUTION BEHIND A RECTANGULAR WING AT A MACH NUMBER OF 2.41"

NACA RM-L50G12, 1957, Langley Aeronautical Lab., Langley Field, VA

An investigation of the nature of the flow field behind a rectangular wing of circular arc cross section has been conducted in the Langley 9-inch supersonic tunnel. Pitot- and static-pressure surveys covering a region of flow behind the wing have been made together with detailed pitot surveys throughout the region of the wake. In addition, the flow direction has been measured by means of a

weathercocking vane. Theoretical calculations have been made to obtain the variation of both downwash and sidewash with angle of attack by using the superposition method of Lagerstrom, Graham, and Grosslight. In addition, the effect of wing thickness on the sidewash with the wing at 0 degree angle of attack has been evaluated.

Adamson, H. P. and Morrison, C. F.

"INFRARED AIRBORNE AND GROUND DETECTION OF WAKE VORTICES"

Proceedings of Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, MA, June 1992,

pp. 43-1 - 43-25

Considerable study of aircraft wake vortices has resulted in a large database on these events. However, little useful data exists for the Infrared (IR) community to study. This paper will assess the feasibility and practicality of Infrared detection of these events. The method will be described. The modelling and field data will be presented. The conclusion is that a dedicated program consisting of additional modelling along with a field data collection program is warranted.

Adrian, R. J., Christensen, K. T. and Liu, Z.-C.

"ANALYSIS AND INTERPRETATION OF INSTANTANEOUS TURBULENT VELOCITY FIELDS"

Experiments in Fluids, Vol. 29, 2000, pp. 275-290.

Methods of analyzing and interpreting velocity-field data (both two- and three-dimensional) to understand the kinematics, dynamics, and scales of turbulence are discussed. Reynolds decomposition and vorticity are traditionally used; however, several other methods, including Galilean (constant convection velocity) and LES decompositions (low-pass filtering), in conjunction with critical-point analysis of the local velocity gradient tensor, reveal more about the structure of turbulence. Once the small-scale structures have been identified, it is necessary to assess their importance to the overall dynamics of the turbulence by visualizing the motions they induce and the stresses they impose on other small-scale vortices and on the large-scale field.

Afanasyev, Y. D. and Korabel, V. N.

"WAKES AND VORTEX STREETS GENERATED BY TRANSLATING FORCE AND FORCE DOUBLET: LABORATORY EXPERIMENTS"

J. Fluid Mech., Vol. 553, 2006, pp. 119-141

Wakes and vortex streets such as those occurring behind towed or self-propelled bodies are generated by moving localized forces in a viscous fluid at moderate values of the Reynolds number. The forcing is provided by an electromagnetic method and allows us to create a 'virtual' body without

introducing any solid objects into the fluid. Characteristics of stable and unstable wakes, particularly the shedding frequency, are measured in the space of control parameters, namely the magnitude of the forcing and the speed of translational motion of the forcing. The results for a single force presented in the dimensionless form of the Strouhal number demonstrate quantitative similarity to those for the classical flow around a cylinder. The problem considered here has an extra degree of freedom compared to the problem of the flow around a cylinder and exhibit a wider array of different regimes. These regimes are documented in both our visualization experiments and particle image velocimetry measurements.

Agnew, P.

"METEOROLOGICAL ASPECTS OF WAKE RELATED CAPACITY GAINS"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

The capacity gains anticipated from reductions in wake vortex related spacings are heavily dependent on the skill of forecasting local meteorological conditions. Two classes of weather are particularly important for reduction of the wake vortex threat: cross winds and turbulence. Climatological studies at Heathrow airport have been carried out to investigate the scope for the introduction of reduced spacing rules. An investigation into the influence of winds on aircraft arrival rates have demonstrated the value of high-quality wind forecasting even for normal operations. Profiles of eddy dissipation rates (EDR) from aircraft descents logged in the Heathrow Database (HDB) have been analyzed to investigate the prospects for improved forecasting of turbulence. Finally, results are presented of a study into actual wake vortex encounters in the HDB. Meteorological and aircraft related parameters have been combined to produce a detailed 'snapshot' of a set of around 30 encounters. It is hoped these will provide a basis for further, more detailed studies.

Agnew, P. and Hoad, D. J.

"CLIMATOLOGY STUDY OF WORLD AIRPORTS IN THE CONTEXT OF WAKE VORTEX BEHAVIOR CLASS"

S-Wake Technical Note 132_1, March 2002, Met Office, Bracknell, UK.

Atmospheric conditions play a key role in the evolution of aircraft wake vortices. Earlier work in S-Wake has proposed the introduction of discrete 'wake vortex behavior classes' (WVBC) in which vortices are expected to exhibit differing evolution characteristics. As part of a broader study, we have established climatologies with respect to these WVBC for a variety of airports world-wide. The Met Office Site Specific Forecast Model was used to calculate vertical profiles of meteorological variables over a seven-year period. Synoptic data from each site and forcing data from the ECMWF ERA-15 re-analysis project were used as input to the model. The profiles were used to evaluate the mean WVBC at each site on pressure levels up to a value corresponding to a height of around 2 km. It is found that at many airports, WVBC which favor the rapid dissipation of wake vortices are prevalent for in excess of

30 percent of the time. The implications of these results for future wake vortex separation rules are discussed. [Company Confidential].

Agnew, P. and Hoad, D. J.

"CLIMATOLOGY STUDY OF WORLD AIRPORTS IN THE CONTEXT OF WAKE VORTEX BEHAVIOR CLASS"

13th AMS Conference on Applied Climatology, Paper J1.10, May 2002, Portland, OR

The increasing capacity demands at major airports throughout the world continue to drive research in the civil aviation community into ways of increasing the number of hourly aircraft movements in a safe manner. At busy airports the frequency of movements is restricted by aircraft separation rules imposed due to safety concerns associated with wake vortex encounters. The current separation rules have been highly effective in reducing wake vortex encounters, however there are situations where they appear overly conservative. As a result there is considerable interest in developing a greater understanding of wake vortex evolution in order that a more flexible approach to imposing separations can be implemented. The European S-Wake is a multi-activity research program aimed at addressing these issues and comprises a variety of both experimental and theoretical studies. One important strand is concerned with understanding how local meteorological conditions influence the evolution of vortices. If meteorological conditions can be identified in which wake vortices are known to either dissipate quickly or be swept away from the path of following aircraft, and if those conditions can be reliably forecast sufficiently far ahead, then there exists the basis for a more flexible implementation of aircraft separation rules, which could lead to valuable increases in the frequency of movements in and out of busy airports. This paper describes work concerned with establishing a climatology with respect to wake vortex behavior classes prevalent at any given time. Here we give detailed results available for some major European airports.

Agnew, P., Lunnon, B., Hoad, D., Frech, M., Gerz, T., Carriere, J.-M. and de Bruin, A.

"WAKE VORTEX ALLEVIATION STRATEGIES FOCUS ON INFLUENCE OF WEATHER ON VORTEX BEHAVIOUR"

ICAO Journal, Vol. 56, No. 7, September 2001, pp. 8-10, 28

Current aircraft separation requirements are effective in preventing wake vortex encounters, but are often overly conservative. Scientists are studying vortex behavior in all weather conditions to determine whether separation requirements may be relaxed under certain circumstances.

Agrawal, A.

"MEASUREMENT OF SPECTRUM WITH PARTICLE IMAGE VELOCIMETRY"

Experiments in Fluids, Vol. 39, 2005, pp. 836-840.

The purpose of this paper is to show that the measurement of turbulent spectrum using whole-field velocity techniques such as particle image velocimetry (PIV) is possible. Toward this end, data from the axial plane of a self-similar turbulent axisymmetric jet, at a Reynolds number, based on Taylor microscale of 30 has been analyzed. The two-dimensional velocity data are first high-pass filtered, which reduces the vortices. An automated method is then used to identify the vortices and measure their properties. By directly measuring the energy of the vortices, it is possible to plot the turbulence spectrum. The spectrum presented here shows the presence of energy containing and inertial regimes. However, the smallest scales have not been resolved in the measurements. The slope of the spectrum in the inertial subrange is about -1.6. The number of vortices in the two regimes have also been measured. The number of vortices in the energy containing regime is substantially smaller than those in the inertial subrange. The technique has been verified by analyzing another dataset. These results show that the direct measurement of vortex properties with reasonable confidence is possible using PIV and an appropriate vortex eduction technique.

Agui, J. H. and Andreopoulos, Y.

"AN EXPERIMENTAL STUDY OF THE INTERACTION OF A LONGITUDINAL VORTEX WITH A TRAVELING SHOCK WAVE"

AIAA Paper No. 1999-0149, Reno, NV, January 1999.

The interaction of a planar shock wave with an induced, wing tip generated, vortical flow has been investigated experimentally in the CCNY Shock Tube Research Facility (STURF). A half span NACA-0012 wing at 15 degrees angle of attack generated the vortex in incident flow Mach numbers of 0.31 to 0.45. Measurements of time-dependent total pressure, total temperature, and three-dimensional velocity and vorticity were carried out in the vortex core region. From an analysis of the data before the interaction, it was found that the core exhibited a well-defined total pressure deficit and an increase in mass flux, indicating a well-structured vortex. Mean vorticity and fluctuations were quite significant before and after the interaction with the shock, providing unprecedented experimental data of this kind. Significant enhancement of vorticity fluctuations after the shock interaction were observed in both cases, with increases in rms value of more than 2-fold. A particle flow visualization technique was employed and revealed quite clearly that the core is well defined before the interaction and then becomes diffused with a core growth of approximately 15 degrees shortly after interaction.

Ahlbrecht, M., Gurke, T. and Pertzsch, B.

"RISK ANALYSIS OF THE PROGNOSIS ALGORITHM AND THE OPERATIONAL USE OF THE WAKE VORTICES WARNING SYSTEM"

B-IT 1029/02, October 1994, DFS Deutsche Flugsicherung, Ottobrunn, Germany

A risk analysis is necessary for the operational use of the wake vortices warning system at Frankfurt Main airport. The results of the risk analysis are presented in this report. The calculated probabilities of forecasting errors are combined with the results of other studies. Using this method, it was possible

to estimate the probability of an accident caused by wake vortices during the operational use of the wake vortices warning system. It is shown that this probability is lower than the accepted risk of single runway operation using wake vortex separation. [In German]

Ahlin, G. A. and Brown R. E.

"PREDICTING THE ONSET OF THE VORTEX RING STATE UNDER ACCELERATED FLIGHT CONDITIONS"

61st Annual National Forum, American Helicopter Society, Grapevine, TX, June 2005

A general method for predicting the onset of the vortex ring state is developed in terms of a model for the propagation and growth of disturbances within the rotor flow. Newman et al.'s engineering model for the onset of the vortex ring state under quasi-steady conditions is shown to be a special case of this approach. A generalization of Newman et al.'s model to the unsteady case is shown to reproduce earlier findings that the onset of the vortex ring state should be postponed to higher descent rates under accelerated flight conditions. Numerical simulations of the onset of the vortex ring state reveal though that the transition into the vortex ring state becomes increasingly gradual as the acceleration of the rotor is increased. Under a combination of high forward speed and vertical acceleration, the vortex ring state may even be replaced by a qualitatively different, highly transient state where the collapse of the wake into the toroidal form that is usually associated with the onset of this flow condition is suppressed. The absence of an abrupt and universal transition marking the onset of the vortex ring state under accelerated flight conditions complicates the application of simple analytical models and implies that the specific details of the time-dependent dynamics of the rotor wake and its interaction with the rotor cannot be ignored when modelling the onset of this flow regime.

Ahlin, G. A. and Brown, R. E.

"WAKE STRUCTURE AND KINEMATICS IN THE VORTEX RING STATE"

Journal of the American Helicopter Society, Vol. 54, No. 3, 2010, pp. 032003-1 - 032003-18.

High-resolution computational simulations of the vortical wake of a rotor operating both near to and within the vortex ring state have been conducted using Brown's vorticity transport model. The nonlinear vortex kinematics of the wake is exposed using three-dimensional visualizations of the simulated flow field. To reveal the vortex dynamics that underpin the highly unsteady flow within the vortex ring state, a rotor with just one blade was modeled. This blade was decoupled aerodynamically from the surrounding velocity field so that it acted merely as a source of trailed vorticity. The investigation identified a significant change in the dominant dynamics of the wake as it swapped from the tubular form that is characteristic of hover or very low speed descent into the toroidal geometry of the vortex ring state. Initial vortex 'pairing' leads to rotation of vortex filaments away from their original attitude. This phenomenon plays an important role in regulating the downwash that the rotor can produce and thus in precipitating the onset of the vortex ring state. The considerable and persistent coherence of the vortical structure of the wake when in the vortex ring state is revealed, despite these disturbances, as are the mechanisms that lead to both small-scale and large-scale wake breakdown

events. Simulations show the balance between the vortex pairing and short-wave instability modes to be different in the vortex ring state at high descent speed, where the wake lies above the rotor, compared to in the vortex ring state at low descent speed when the wake lies predominantly below the rotor. This yields subtle differences to the kinematics and structure of the wake in the two cases.

Ahlin, G. A. and Brown, R. E.

"INVESTIGATING THE PHYSICS OF ROTOR VORTEX RING STATE USING THE VORTICITY TRANSPORT MODEL"

31st European Rotorcraft Forum, Florence, Italy, September 2005

Some of the root causes of the behavior of a helicopter rotor in the vortex ring state are investigated using simulations, conducted using Brown's Vorticity Transport Model, of a two-bladed teetering rotor descending into the vortex ring state under conditions of constant collective pitch. Contrary to some previous reports, the onset of thrust settling on the rotor is found to occur at descent rates much lower than that at which the wake breaks down into the toroidal form that is characteristic of the fully developed vortex ring state. Thrust settling is caused by a loss of loading on the outboard parts of the rotor that is induced initially by compression of the wake below the rotor during low-speed descent. The behavior of the rotor in the vortex ring state appears to be practically insensitive to the twist of the blades, at least for rotors with moderate levels of blade twist. Although blade stall has little effect on the onset of the vortex ring state, it is quite likely that stall on the inner parts of the rotor, even for rotors with moderate levels of blade twist, may modify significantly the behavior of the system during the later stages of the development of the vortex ring state.

Ahmad, J. and Biedron, R. T.

"CODE-TO-CODE COMPARISON OF CFD/CSD SIMULATION FOR A HELICOPTER ROTOR IN FORWARD FLIGHT"

AIAA Paper 2011-3819, June 2011, Honolulu, Hawaii.

Two unsteady Reynolds-averaged Navier-Stokes solvers are used to compute the rotor air loads on the UH-60A rotorcraft at several flight conditions across the flight envelope. One code, OVERFLOW, solves the flow equations using either structured grids, or a combination of structured and Cartesian grids. The other solver, FUN3D, uses unstructured grids. Both flow solvers are coupled to the same rotorcraft comprehensive code (CAMRAD II) in order to account for trim and aeroelastic deflections, and both utilize the same loose coupling scheme to transfer data between the flow solver and the comprehensive code. In the process of performing the code-to-code comparison, several small but important details are examined that may sometimes be overlooked when comparing results from rotorcraft simulations using different codes. Computed normal force, pitching moment, and chord force are compared between codes, and also with flight data.

Ahmad, J. U., Yamauchi, G. K. and Kao, D. L.

"COMPARISON OF COMPUTED AND MEASURED VORTEX EVOLUTION FOR A UH-60A ROTOR IN FORWARD FLIGHT"

AIAA Paper 2013-3160, June 2013, San Diego, CA.

A Computational Fluid Dynamics (CFD) simulation using the Navier-Stokes equations was performed to determine the evolutionary and dynamical characteristics of the vortex flow field for a highly flexible aeroelastic UH-60A rotor in forward flight. The experimental wake data were acquired using Particle Image Velocimetry (PIV) during a test of the full-scale UH-60A rotor in the National Full-Scale Aerodynamics Complex 40- by 80-Foot Wind Tunnel. The PIV measurements were made in a stationary cross-flow plane at 90 deg rotor azimuth. The CFD simulation was performed using the OVERFLOW CFD solver loosely coupled with the rotorcraft comprehensive code CAMRAD II. Characteristics of vortices captured in the PIV plane from different blades are compared with CFD calculations. The blade air loads were calculated using two different turbulence models. A limited spatial, temporal, and CFD/comprehensive-code coupling sensitivity analysis was performed in order to verify the unsteady helicopter simulations with a moving rotor grid system.

Ahmad, N. N. and Proctor, F. H.

"ESTIMATION OF EDDY DISSIPATION RATES FROM MESOSCALE MODEL SIMULATIONS"

AIAA Paper No. 2012-0429, January 2012, Nashville, Tennessee.

The Eddy Dissipation Rate is an important metric for representing the intensity of atmospheric turbulence and is used as an input parameter for predicting the decay of aircraft wake vortices. In this study, the forecasts of eddy dissipation rates obtained from the current state-of-the-art mesoscale model are evaluated for terminal area applications. The Weather Research and Forecast mesoscale model is used to simulate the planetary boundary layer at high horizontal and vertical mesh resolutions. The Bougeault-Lacarrere and the Mellor-Yamada-Janjic schemes implemented in the Weather Research and Forecast model are evaluated against data collected during the National Aeronautics and Space Administration's Memphis Wake Vortex Field Experiment. Comparisons with other observations are included as well.

Ahmad, N. N. and Pruis, M. J.

"EVALUATION OF FAST-TIME WAKE MODELS USING DENVER 2006 FIELD EXPERIMENT DATA"

AIAA Paper 2015-3318, June 2015, Dallas, TX.

The National Aeronautics and Space Administration conducted a series of wake vortex field experiments at Denver in 2003, 2005, and 2006. This paper describes the lidar wake vortex measurements and associated meteorological data collected during the 2006 deployment, and includes results of recent reprocessing of the lidar data using a new wake vortex algorithm and estimates of the atmospheric turbulence using a new algorithm to estimate eddy-dissipation rate from the lidar data.

The configuration and set-up of the 2006 field experiment allowed out-of-ground effect vortices to be tracked in lateral transport further than any previous campaign and thereby provides an opportunity to study long-lived wake vortices in moderate to low crosswinds. An evaluation of NASA's fast-time wake vortex transport and decay models using the dataset shows similar performance as previous studies using other field data.

Ahmad, N. N., Proctor, F. H. and Perry, R. B.

"NUMERICAL SIMULATION OF THE AIRCRAFT WAKE VORTEX FLOWFIELD"

AIAA Paper 2013-2552, June 2013, San Diego, CA.

The near-wake vortex flow field from a NACA0012 half-wing was simulated using a fully unstructured Navier-Stokes flow solver in three dimensions at a chord Reynolds number of 4.6 million and a Mach number of approximately 0.15. Several simulations were performed to examine the effects of boundary conditions, mesh resolution, and turbulence scheme on the formation of wingtip vortex and its downstream propagation. The standard Spalart-Allmaras turbulence model was compared with the Dacles-Mariani and Spalart-Shur corrections for rotation and curvature effects. The simulation results were evaluated using the data from an experiment performed at NASA Ames' 32in x 48in low speed wind tunnel.

Ahmad, N. N., Proctor, F. H., Duparcmeur, F. M. L. and Jacob, D.

"REVIEW OF IDEALIZED AIRCRAFT WAKE VORTEX MODELS"

AIAA Paper 2014-0927, January 2014, National Harbor, MD.

Properties of three aircraft wake vortex models, Lamb-Oseen, Burnham-Hallock, and Proctor are reviewed. These idealized models are often used to initialize the aircraft wake vortex pair in large eddy simulations and in wake encounter hazard models, as well as to define matched filters for processing lidar observations of aircraft wake vortices. Basic parameters for each vortex model, such as peak tangential velocity and circulation strength as a function of vortex core radius size, are examined. The models are also compared using different vortex characterizations, such as the vorticity magnitude. Results of Euler and large eddy simulations are presented. The application of vortex models in the post-processing of lidar observations is discussed.

Ahmad, N. N., Proctor, F. H., VanValkenburg, R. L., Pruis, M. J. and Duparcmeur, F. M. L.

"MESOSCALE SIMULATION DATA FOR INITIALIZING FAST-TIME WAKE TRANSPORT AND DECAY MODELS"

AIAA Paper 2013-0510, January 2013, Grapevine, TX.

The fast-time wake transport and decay models require vertical profiles of crosswinds, potential temperature, and the eddy dissipation rate as initial conditions. These inputs are normally obtained from various field sensors. In case of data-denied scenarios or operational use, these initial conditions

can be provided by mesoscale model simulations. In this study, the vertical profiles of potential temperature from a mesoscale model were used as initial conditions for the fast-time wake models. The mesoscale model simulations were compared against available observations and the wake model predictions were compared with the Lidar measurements from three wake vortex field experiments.

Ahmad, N. N., VanValkenberg, R. L., Bowles, R. L., Duparcmeur, F. M. L., Gloudemans, T., van Lochem, S. and Ras, E.

"EVALUATION OF FAST-TIME WAKE VORTEX MODELS USING WAKE ENCOUNTER FLIGHT TEST DATA"

AIAA Paper 2014-2466, June 2014, Atlanta, GA.

This paper describes a methodology for the integration and evaluation of fast-time wake models with flight data. The National Aeronautics and Space Administration conducted detailed flight tests in 1995 and 1997 under the Aircraft Vortex Spacing System Program to characterize wake vortex decay and wake encounter dynamics. In this study, data collected during Flight 705 were used to evaluate NASA's fast-time wake transport and decay models. Deterministic and Monte-Carlo simulations were conducted to define wake hazard bounds behind the wake generator. The methodology described in this paper can be used for further validation of fast-time wake models using en-route flight data, and for determining wake turbulence constraints in the design of air traffic management concepts.

Ahmad, N. N., VanValkenburg, R. L., Pruis, M. J. and Limon Duparcmeur, F. M.

"NASA AVOSS FAST-TIME MODELS FOR AIRCRAFT WAKE PREDICTION: USER'S GUIDE (APA3.8 AND TDP2.1)"

NASA-TM-2016-219353, January 2016, NASA Langley Research Center, Hampton, VA.

NASA's current distribution of fast-time wake vortex decay and transport models includes APA (Version 3.8) and TDP (Version 2.1). This User's Guide provides detailed information on the model inputs, file formats, and model outputs. A brief description of the Memphis 1995, Dallas/Fort Worth 1997, and the Denver 2003 wake vortex datasets is given along with the evaluation of models. A detailed bibliography is provided which includes publications on model development, wake field experiment descriptions, and applications of the fast-time wake vortex models.

Ahmad, N., Barmore, B. and Swieringa, K.

"WIND INFORMATION UPLINK TO AIRCRAFT PERFORMING INTERVAL MANAGEMENT OPERATIONS"

AIAA Paper 2015-3398, June 2015, Dallas, TX.

The accuracy of the wind information used to generate trajectories for aircraft performing Interval Management (IM) operations is critical to the success of an IM operation. There are two main forms of uncertainty in the wind information used by the Flight Deck Interval Management (FIM) equipment. The first is the accuracy of the forecast modeling done by the weather provider. The second is that only

a small subset of the forecast data can be uplinked in the aircraft for use by the FIM equipment, resulting in loss of additional information. This study focuses on what subset of forecast data, such as the number and location of the points where the wind is sampled should be made available to uplink to the aircraft.

Ahmad, N.N., Proctor, F.H., Limon Duparcmeur, F., and Jacob, D.

"Review of Idealized Aircraft Wake Vortex Models"

AIAA Paper No. 2014-0927, January 2014, National Harbor, Maryland

Properties of three aircraft wake vortex models, Lamb-Oseen, Burnham-Hallock, and Proctor are reviewed. These idealized models are often used to initialize the aircraft wake vortex pair in large eddy simulations and in wake encounter hazard models, as well as to define matched filters for processing lidar observations of aircraft wake vortices. Basic parameters for each vortex model, such as peak tangential velocity and circulation strength as a function of vortex core radius size, are examined. The models are also compared using different vortex characterizations, such as the vorticity magnitude. Results of Euler and large eddy simulations are presented. The application of vortex models in the post-processing of lidar observations is discussed.

Ahmad, N.N., VanValkenburg, R.L., and Pruis, M.J.

"NASA AVOSS FAST-TIME WAKE PREDICTION MODELS: USER'S GUIDE, NASA Technical Memorandum NASA/TM-2014-218152"

The National Aeronautics and Space Administration (NASA) is developing and testing fast-time wake transport and decay models to safely enhance the capacity of the National Airspace System (NAS). The fast-time wake models are empirical algorithms used for real-time predictions of wake transport and decay based on aircraft parameters and ambient weather conditions. The aircraft dependent parameters include the initial vortex descent velocity and the vortex pair separation distance. The atmospheric initial conditions include vertical profiles of temperature or potential temperature, eddy dissipation rate, and crosswind. The current distribution includes the latest versions of the APA (3.4) and the TDP (2.1) models. This User's Guide provides detailed information on the model inputs, file formats, and the model output. An example of a model run and a brief description of the Memphis 1995 Wake Vortex Dataset is also provided.

Ahmad, S., Brewer, W. H. and Cinnella, P.

"AN ACCURATE UNSTRUCTURED SIMULATION OF WINGTIP VORTEX"

AIAA Paper 2009, Jan. 2009, Orlando, FL.

Sophisticated techniques for unstructured simulation of a wingtip vortex were developed and demonstrated on stationary NACA0012 airfoil. The techniques were also exemplified for flapping wing

propulsion. Flow parameters were computed at 40 percent chord length downstream to study near field behavior of the vortex. A good agreement of tangential velocity along the vortex core with experimental data was achieved. Surface pressure coefficient, vortex core pressure and vortex diffusion were also found matching with experimental data.

Ahmadi, A. R.

"AN EXPERIMENTAL INVESTIGATION OF BLADE-VORTEX INTERACTION AT NORMAL INCIDENCE"

J. Aircraft, Vol. 23, No. 1, January 1986, pp. 47-55

Blade-vortex interaction (BVI) near and away from the blade tip was experimentally investigated for normal incidence where the vortex is generally parallel to the rotor axis. The experiment was designed to be representative of the chopping of helicopter main rotor tip vortices by the tail rotor. Tip Mach number, radial BVI station, and freestream velocity were varied. Fluctuating blade pressures, far-field sound pressure level and directivity, velocity field of the vortex, and BVI angles were measured. BVI produced impulsive noise and impulsive pressures near the blade leading edge. The radiation pattern for BVI away from the tip was that of a dipole, with the direction of minimum radiation, previously found to be in the plane of the blade, rotated considerably in the direction of negative angle of attack. This is believed to be due to unsteady drag radiation caused by stronger BVIs in the present study. For BVI near the tip, the intensity of the interaction was reduced and the radiation pattern was more complex. Away from the tip, the peak amplitude of fluctuating pressure on the suction side of the blade (near the leading edge) was larger than that on the pressure side, as expected due to the effect of compressibility. This trend was reversed near the tip.

Ahmadi-Baloutaki, M., Carriveau, R. and Ting, D. S.-K.

"AN EXPERIMENTAL STUDY ON THE INTERACTION BETWEEN FREE-STREAM TURBULENCE AND A WING-TIP VORTEX IN THE NEAR-FIELD"

Aerospace Science and Technology, Vol. 43, 2015, pp. 395-405.

The effect of external free-stream turbulence was investigated experimentally in the near-field of a wing-tip vortex. A free-stream turbulent flow with 4.6 percent turbulence intensity was created with the aid of a grid turbulence generator, while the turbulence intensity in the base flow case with no grid was approximately 0.5 percent. The experiments were conducted in a closed-circuit wind tunnel while a dynamic force transducer was used to measure the aerodynamic forces on a NACA 0015 wing section in the range of 0 to 25 degrees angle of attack. The wing section with a semi-span aspect ratio of 5.4 spanned approximately half height of the wind tunnel section and fixed vertically to the load cell at the base. Hot-wire anemometry was used to measure the velocity field downstream of the wing at crossflow planes of $x/c = 0.1, 0.42, 0.77$ and 1.03 while the Reynolds number and angle of attack were set at 160,000 and 10 degrees, respectively. The results of aerodynamic force measurement for the no-grid case agree fairly with other experimental and analytical works. In addition, circumferential velocity and circulation profiles inside the vortex flow-field fit well with analytical expressions proposed by

others. The crossflow velocity contours show that the free-stream turbulence tends to increase the vortex diffusion at $x/c = 0.77$ and 1.03 . The inboard and upward movement of the tip vortex downstream of the wing was not significantly affected by the introduction of free-stream turbulence, while external free-stream turbulence increases the turbulence intensity peak. External turbulence also increased the circumferential velocity and vortex circulation with respect to the streamwise distance at radial locations far from the vortex center.

Airbus Industries

"STUDY FOCUSES ON WAKE VORTEX PRODUCED BY DIFFERENT AIRBUS MODELS"

ICAO Journal, Vol. 53, No. 4, May 1998, p. 26

An Airbus Industry sponsored research project which used a ground-based laser to measure the wake vortex left behind each of the manufacturer's aircraft is reviewed. The use of the information gathered during the study in designing future aircraft such as the Airbus A3XX is addressed.

Aitken, M. L., Banta, R. M., Pichugina, Y. L. and Lundquist, J. K.

"QUANTIFYING WIND TURBINE WAKE CHARACTERISTICS FROM SCANNING REMOTE SENSOR DATA"

Journal of Atmospheric and Oceanic Technology, Vol. 31, April 2014, pp. 765-787.

Because of the dense arrays at most wind farms, the region of disturbed flow downstream of an individual turbine leads to reduced power production and increased structural loading for its leeward counterparts. Currently, wind farm wake modeling, and hence turbine layout optimization, suffers from an unacceptable degree of uncertainty, largely because of a lack of adequate experimental data for model validation. Accordingly, nearly 100 h of wake measurements were collected with long-range Doppler lidar at the National Wind Technology Center at the National Renewable Energy Laboratory in the Turbine Wake and Inflow Characterization Study (TWICS). This study presents quantitative procedures for determining critical parameters from this extensive dataset - such as the velocity deficit, the size of the wake boundary, and the location of the wake centerline - and categorizes the results by ambient wind speed, turbulence, and atmospheric stability. Despite specific reference to lidar, the methodology is general and could be applied to extract wake characteristics from other remote sensor datasets, as well as computational simulation output. The observations indicate an initial velocity deficit of 50-60 percent immediately behind the turbine, which gradually declines to 15-25 percent at a downwind distance x of 6.5 rotor diameters (D). The wake expands with downstream distance, albeit less so in the vertical direction due to the presence of the ground: initially the same size as the rotor, the extent of the wake grows to $2.7D$ ($1.2D$) in the horizontal (vertical) at $x = 6.5D$. Moreover, the vertical location of the wake center shifts upward with downstream distance because of the tilt of the rotor.

Akbulut, M., Gupta, S. and Verdun, H.

"FIBER LASER COHERENT LIDAR FOR WAKE-VORTEX HAZARD DETECTION"

16th Coherent Laser Radar Conference, Long Beach, CA, June 2011.

We demonstrated a 1.55-micron fiber-optic coherent lidar system with greater than 500 microjoules energy at 25 kHz and about 1.5 MHz Doppler linewidth. We believe this lidar has the potential for aviation applications such as airborne wake-vortex detection.

Akbulut, M., Hwang, J., Kimpel, F., Gupta, S. and Verdun, H.

"PULSED COHERENT FIBER LIDAR TRANSCEIVER FOR AIRCRAFT IN-FLIGHT TURBULENCE AND WAKE-VORTEX HAZARD DETECTION"

Proceedings SPIE, Vol. 8037, Laser Radar Technology and Applications XVI, June 2011, pp. 80370R-1 - 80370R-10.

We report on the development of a fiber-optic pulsed coherent lidar transceiver for wind-velocity and aircraft wake-vortex hazard detection. The all-fiber 1.5-micron transmitter provides up to 560 microjoule energy at 25 kHz with 800 ns pulse width (pump limited). Performance simulations indicate wake-vortex hazard signature detection up to about 2.5 km range with a receiver sensitivity of about 2 fW (SNR=6), suited for an aircraft landing scenario. Furthermore, the transceiver is implemented using a high-speed FPGA based control and digital-signal-processing, enabling its use as a flexible pulse-format multi-function in-flight lidar sensor. We present the latest laboratory results and preliminary testing of this pulsed coherent lidar transceiver, along with the lidar performance simulation of wake-vortex eddy models.

Akhmetov, D. G., Nikulin, V. V. and Petrov, V. M.

"EXPERIMENTAL STUDY OF SELF-OSCILLATIONS DEVELOPING IN A SWIRLING-JET FLOW"

Fluid Dynamics, Vol. 39, No. 3, 2004, pp. 406-413

The results of an experimental investigation of the periodic pressure oscillations developing in a submerged swirling jet flowing out into an open space are presented. The main governing parameters of the process are determined and a general dependence relating the oscillation frequency with the governing parameters over a wide range of parameter variation is established experimentally. Based on this dependence, an empirical formula for calculating the oscillation frequency is proposed.

Akinjanju, T.

"GROUND EVALUATION OF SEEDING AN IN-FLIGHT WINGTIP VORTEX USING INFRARED IMAGING FLOW VISUALIZATION TECHNIQUE"

NASA/American Soc. Eng. Education Summer Faculty Fellowship Program, September 1989, Old Dominion Univ., Norfolk, VA, pp. 38-40

An experimental simulation of an in-flight wingtip vortical flow visualization technique uses infrared imaging to observe strong and concentrated vortices. This experiment is phase 1 of a two-phase infrared evaluation program. The system includes a vortex generator (model 320 Vortec Vortex Tube) which generates the required vortex. The mouth of the unit is mounted close to the free end of a half-inch diameter, sixteen and a half foot long stainless-steel tubing (sized after tubing currently installed in the wings of an experimental Beechcraft Sundowner 180 aircraft). Dichloro difluoromethane (Freon-12) is entrained into the generated vortex. A breakdown of the vortices is indicated by the rapid diffusion and the resulting pattern is tracked using the infrared imager and video systems. Flow rates (volume and mass) are estimated at the laboratory and proposed flight conditions. The nominal flight altitude is expected to be 2500 feet.

Akinyanju, T.

"GROUND EVALUATION OF SEEDING AN IN-FLIGHT WINGTIP VORTEX USING INFRARED IMAGING FLOW VISUALIZATION TECHNIQUE"

NASA CR-181894, September 1989, Norfolk State University, Norfolk, VA.

An experimental simulation of an in-flight wingtip vortical flow visualization technique uses infrared imaging to observe strong and concentrated vortices. This experiment is phase I of a two-phase infrared evaluation program. The system includes a vortex generator (model 320 Vortec Vortex Tube) which generates the required vortex. The mouth of the unit is mounted close to the free end of a half-inch diameter, sixteen and a half foot long stainless-steel tubing (sized after tubing currently installed in the wings of an experimental Beechcraft Sundowner 180 aircraft). Dichloro difluoromethane (Freon-12) is entrained into the generated vortex. A breakdown of the vortices is indicated by the rapid diffusion and the resulting pattern is tracked using the infrared imager and video systems. Flow rates (volume and mass) are estimated at the laboratory and proposed flight conditions. The nominal flight altitude is expected to be 2500 feet.

Aksman, M. I. and Novikov, E. A.

"RECONNECTIONS OF VORTEX FILAMENTS"

Fluid Dynamics Research, Vol. 3, 1988, pp. 239-246.

The process of break-down and reconnection of vortex filaments is considered by the method of three-dimensional vortex singularities (vortons) in various situations, including oblique interaction of a vortex ring with a boundary in shear flow, shedding of a vortex ring from a horseshoe vortex, instability of elliptic vortex ring, Crow instability of two perturbed antiparallel vortex filaments, merging and subsequent splitting of vortex rings. Special attention is paid to the global integrals (vorticity, momentum, angular momentum) and to the inviscid dissipation of energy. The visualization of the effective vortex core, created by the interference of the vorticity fields of vortons, is presented. The

comparisons with other methods of simulation of three-dimensional vortex interactions and with the observations have been made.

Albano, F., De Gregorio, F. and Ragni, A.

"TRAILING VORTEX DETECTION AND QUANTITATIVE EVALUATION OF VORTEX CHARACTERISTICS BY PIV TECHNIQUE"

20th International Congress on Instrumentation in Aerospace Simulation Facilities, August 2003, Gottingen, Germany

This paper summarizes the activities performed to investigate the formation, motion and persistence of trailing vortices released by large commercial aircraft. Two different experimental test campaigns were carried out in two different large towing tank facilities performing PIV measurements. The lesson learned by the first investigation and by the experience of the scientific community, the solution adopted to characterize the wake vortex by the initial formation phase down to wake collapsing in the far-wake region are illustrated. Together with the adopted technical solution, with the selected experimental facility and with the improved measurement system, a particular care is taken: on the data analysis description, on the importance of advanced PIV algorithms and on the selected post-processing methods for evaluating the main magnitudes characterizing the vortex structures.

Albers, A., Janssen, A. W. and Mander, J.

"COMPARISON OF LIDARS, GERMAN TEST STATION FOR REMOTE WIND SENSING DEVICES"

9th German Wind Energy Conference, DEWEK, November 2008, Bremen, Germany.

Deutsche WindGuard is involved in the test of lidar based wind measurement devices since 2005. At current status, there are two lidar systems commercially available, the British ZephIR and the French Windcube system. The Windcube has reached an excellent accuracy, reproducibility, and availability in flat terrain, even at 135m measurement height above ground, while the ZephIR has problems to reach high accuracy in large measurement heights. The German Test Station for Remote Wind Sensing Devices has been initiated to provide the wind industry the possibility to have tested lidars or sodars prior to the application in the field, like cup anemometer calibrations. Furthermore, the test station is intended to be used for the type specific classification of remote wind sensing devices.

Aleksander, B.

"THREE-DIMENSIONAL ROTOR FLOW CALCULATIONS"

FME Transactions, Vol. 33, No.1, 2005, pp. 33-39

This paper presents the numerical model developed for rotor blade aerodynamics loads calculation. The model is unsteady and fully three-dimensional. Helicopter blade is assumed to be rigid, and its motion during rotation is modeled in the manner that rotor presents a model of rotor of helicopter

Aerospatiale SA 341 Gazelle (the blade is attached to the hub by flap, pitch and pseudo lead-lag hinges). Flow field around the blade is observed in succession of several azimuth locations. Flow field around helicopter rotor is modeled as fully three-dimensional, unsteady and potential. Blade aerodynamics is modeled using a lifting surface model. Rotor wake is generated from the straight elements of constant vorticity, released from the trailing edge, at fixed azimuth angles. These vortices represent both trailed and shed wake components, and are allowed to freely convect along local velocity vectors. Wake is modeled as free one, and its shape at certain moment can be calculated from simple kinematics laws applied on collocation points of the wake. Wake distortion is calculated only in the rotor near-field, i.e. in finite number of rotor revolutions. Vortex elements are modeled with vortex core. The radius of the vortex core is assumed independent of time, and it depends on circulation gradient at the point of vortex element released from the blade.

Alekseev, S. V., Baranov, N. A., Belotserkovskiy, A. S. and Kanevskiy, M. I.

"METHOD AND ON-BOARD SYSTEM FOR ENSURING THE MINIMUM LONGITUDINAL SEPARATION DISTANCE UNDER WAKE TURBULENT CONDITIONS"

US Patent 9,466,220 B2, October 2016.

Standardized distance minima for longitudinal separation is ensured during flight of a second aircraft behind a first aircraft on take-off or landing of the aircraft on one runway or on two parallel runways located near to each other, or during flight one behind the other at near altitude levels in condition where there is the risk of turbulence from the vortex wake of the first aircraft possibly being present along the direction of movement of the second aircraft. Continuous monitoring of the level of wake vortex flight safety of the second aircraft is carried out in a buffer zone which surrounds the aircraft and is selected on the basis of the direction of the aircraft outside the standardized distance minimum, taking into account pilot reaction time and the time for the system for controlling the second aircraft to respond to a command to change speed.

Alferov, V. I., Okerblom, T. I. and Sarantsev, A. I.

"EXPERIMENTAL INVESTIGATION OF VORTEX FLOWS NEAR LOW-ASPECT-RATIO WINGS AND CIRCULAR CONES AT MACH TWO"

Akademiia Nauk. SSR, Izvestiia, Mekhanika Zhidkosti i Gaza, September-October 1967, pp. 113-121

Application of a flow-visualization method to the investigation of the flow pattern resulting from the interaction of wing-tip vortices with the boundary layer. The method employed makes use of a stable luminosity that appears (because of a predischage) when a high voltage is applied to electrodes situated in an airflow. Photographs (on which the shock waves from the electrodes and flow separation region are clearly seen against the interelectrode luminosity) showing the trajectories of the vortex streets are obtained for low-aspect-ratio wings and circular cones situated at various angles of attack in a flow with $M=2$ and $Re=0.9 \times 10^6$.

Alford, Jr., W. J.

"THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE SUBSONIC-FLOW FIELDS BENEATH SWEEPED AND UNSWEEPED WINGS WITH TABLES OF VORTEX-INDUCED VELOCITIES"

NACA TR-1327, August 1956, Langley Aeronautical Laboratory, Langley Field, VA

The flow-field characteristics beneath swept and unswept wings as determined by potential-flow theory are compared with the experimentally determined flow fields beneath swept and unswept wing-fuselage combinations. The potential-flow theory utilized considered both spanwise and chordwise distributions of vorticity as well as the wing-thickness effects. The perturbation velocities induced by a unit horseshoe vortex are included in tabular form. The results indicated that significant chordwise flow gradients existed beneath both swept and unswept wings at zero lift and throughout the lift range. The theoretical predictions of the flow-field characteristics were qualitatively correct in all cases considered, although there were indications that the magnitudes of the downwash angles tended to be overpredicted as the tip of the swept wing was approached and that the sidewash angles ahead of the unswept wing were underpredicted. The calculated effects of compressibility indicated that significant increases in the chordwise variation of flow angles and dynamic-pressure ratios should be expected in going from low to high subsonic speeds.

Ali, M. and Abid, M.

"SELF-SIMILAR BEHAVIOUR OF A ROTOR WAKE VORTEX CORE"

Journal of Fluid Mechanics, Vol. 740, 2014, pp. R1-1 to R1-12.

We report a self-similar behavior of solutions (obtained numerically) of the Navier-Stokes equations behind a single-blade rotor. That is, the helical vortex core in the wake of a rotating blade is self-similar as a function of its age. Profiles of vorticity and azimuthal velocity in the vortex core are characterized, their similarity variables are identified and scaling laws of these variables are given. Solutions of incompressible three-dimensional Navier-Stokes equations for Reynolds numbers up to $Re = 2000$ are considered.

Alim, A.

"A PHYSICAL COMPREHENSIVE DEFINITION OF A VORTEX BASED ON THE LAMB VECTOR"

Algerian Journal of Applied Fluid Mechanics, Vol. 1, 2007, pp. 1-5.

Although the concept of a vortex is an essential tool in the comprehension of fluid dynamics, it is still very difficult to find a universal definition for a vortex. In the present study, we elected to propose a simple physical comprehensive definition for a vortex. A vortex is defined using the Lamb vector as a low velocity noisy structure. This new definition has been applied to a theoretical Oseen vortex and to experimental flows obtained from particle image velocimetry (PIV) images. The vortex center was defined as the location of the highest noise source and the vortex core was delimited by the two extrema of the spatial derivative of the divergence of the Lamb vector. A very good correlation was

found between the new method proposed and the standard eigenvalue method. The extension of the method to complex flows was possible by introducing a threshold function. It was, therefore, possible to extract the maximal number of vortex structures from the velocity field.

Alix, D. and Simich, P.

"ACOUSTIC CHARACTERIZATION OF WAKE VORTICES IN-GROUND-EFFECT"

Report, Aero 16.622 Spring 2004, May 2004, MIT, Cambridge, MA.

Recent theoretical work suggests that aircraft wake vortices produce a low frequency acoustic signal when they descend in ground effect. To date, only high frequency signals have been observed, and no studies have been done on acoustic behavior in ground effect. The ability to detect vortices using acoustic methods could lead to reliable vortex sensors for high traffic airports. In this experiment, an array of four directional microphones was used to record acoustic signals from vortices IGE. The data was analyzed with Fast Fourier Transform techniques that revealed the presence of acoustic signals in 6 of the 26 aircraft recorded. Although low frequency background noise made signals hard to detect, the aircraft recorded did show acoustic signals above 500 Hz. One aircraft showed a signal below 200 Hz; however, results for these low frequencies are still inconclusive due to background noise.

Alix, D. C., Simich, P. D., Wassaf, H. and Wang, F. Y.

"ACOUSTIC CHARACTERIZATION OF WAKE VORTICES IN GROUND EFFECT"

AIAA Paper No. 2005-0260, Reno, NV, January 2005

The experience and findings of an exploratory effort to characterize the sound emitted by aircraft wake vortices near the ground are presented. A line array of four directional microphones was deployed and recorded the wakes of several commercial aircraft in the approach phase with particular attention being paid to the characterization of background noise. It is found that vortices near the ground emit broadband sound with frequency contents ranging from below 100 Hz to near 2000 Hz and possibly beyond. However, addressing the degree of consistency of the vortex sound would require deployment of a larger array. The mechanism of vortex sound generation and suggestions on future studies are discussed.

Alksne, A. Y.

"DETERMINATION OF VORTEX PATHS BY SERIES EXPANSION TECHNIQUE WITH APPLICATION TO CRUCIFORM WINGS"

NACA TR-1311, 1957, Ames Aeronautical Laboratory, Moffett Field, CA

A series method of determining two-dimensional vortex paths is considered and applied to the computation of vortex positions behind a slender equal-span cruciform wing at any angle of bank as a function of the distance behind the trailing edge. Calculated paths are shown for four bank angles. For

a bank angle of 45 deg. comparison is made with the results of a closed expression given in NACA TN 2605. For other bank angles water-tank experiments provide qualitative comparison. Satisfactory agreement is found for a sufficient distance downstream to include most practical missile-tail positions. The interference forces on an equal-span interdigitated cruciform tail behind a slender equal-span cruciform wing are calculated for four angles of bank from the vortex positions found by use of the series.

Al-Kuran, H., Coronado, P., Ilie, M. and Zha, G.-C.

"HIGH ANGLE OF ATTACK HELICOPTER BLADE-VORTEX INTERACTION; NUMERICAL STUDIES USING LES"

AIAA Paper No. 2011-3208, June 2011, Honolulu, Hawaii.

The influence of angle of attack on the helicopter blade-vortex mechanism of interaction is investigated using large eddy simulation (LES). The LES technique provides a promising tool for obtaining the unsteady wall-pressure fields, aerodynamic coefficients, and the acoustic source functions. A large eddy simulation is carried out for a two-dimensional Blade-Vortex Interaction problem, for a chord-based Reynolds number of 1300000. Computations are carried out to investigate the influence of angle of attack (0, 5 and 10 degrees) on the aerodynamic coefficients and acoustic field.

Allan, S. S. and Dacey, T. J.

"AN ANALYSIS OF THE IMPACTS OF WAKE VORTEX RESTRICTIONS AT LGA"

Report ATC-305, Sept. 2002, MIT Lincoln Laboratory, Lexington, MA.

Wake vortex restrictions at New York's La Guardia airport cause a significant reduction in capacity when aircraft land on runway 22 and depart on runway 31. This report presents an analysis of the annual delay cost at LGA associated with the wake vortex restrictions. We find that the delay due to these restrictions exceeds 4000 hours annually, and that these restrictions cause a significant workload increase to controllers at both La Guardia and the New York TRACON. If traffic levels were to increase 10 percent from their February 2001 levels, the corresponding increase in delay due to the wake vortex restrictions would rise from 30 hours a day to over 400 hours a day in this runway configuration. It is also found that for a meaningful increase in passenger capacity in this runway configuration to be achieved as demand grows, restrictions must be reduced from their current levels. If the percentage of heavy/757s doubled at LGA, there would be no increase in passenger capacity while daily delays in this runway configuration due to current wake vortex separation standards would increase by 250 hours.

Allen, A. and Breitsamter, C.

"INVESTIGATION ON AN ACTIVE WINGLET INFLUENCING THE WAKE OF A LARGE TRANSPORT AIRCRAFT"

ICAS 2006, Paper 2006-3.8.2, Sept. 2006, Hamburg, Germany.

The flow field behind a Very Large Transport Aircraft is investigated at several cross-flow planes. The amplification of instability mechanisms using an active rudder on a large winglet will be discussed. Results will be shown for the baseline and cases of passive and active rudder deflections using hot-wire anemometry.

Allen, A. and Breitsamter, C.

"LANDING GEAR INFLUENCE ON THE WAKE VORTEX OF A LARGE TRANSPORT AIRCRAFT"

Journal of Aircraft, Vol. 45, No. 4, July-August 2008, pp. 1367-1372.

An experimental investigation on the wake vortex formation and evolution of a four-engine large transport aircraft model in the near field and extended near field has been conducted by means of hot-wire anemometry in a wind tunnel. The half-model used has a scale of 1:19.25 and the tests focus on the high-lift case of a typical landing configuration at a Reynolds number of 520,000 based on the wing mean aerodynamic chord. The flow field is investigated up to 4.7 spans downstream of the model, which is investigated with and without landing gear. Based on the measured time-dependent velocity components, the wake flow field is analyzed by distributions of vorticity, turbulence intensities, and spectral densities. The landing gear consists of a stay and four wheels, which create a bluff-body wake that interferes with the shear layer caused by the wing and wing junction. The landing gear creates a low-energy vortex system and a highly turbulent wake. Due to the landing gear, the main vortex centers are located slightly further outboard and the roll-up process is retarded, especially the inboard movement of the horizontal tail plane vortex. The velocity spectra of the landing gear wake show broadband characteristics with some moderate narrowband energy concentrations in the close near field, which do not enhance inherent wake instabilities. Although the turbulence caused by the landing gear is still present in the extended near field, only a small influence on the overall vortex system of the entire aircraft can be found. The landing gear influence is therefore negligible in the context of reducing minimum aircraft separation distances.

Allen, A. and Breitsamter, C.

"TRANSPORT AIRCRAFT WAKE INFLUENCED BY A LARGE WINGLET AND WINGLET FLAPS"

J. Aircraft, Vol. 45, No. 2, March-April 2008, pp. 686-699

Detailed flow fields of a wind-tunnel investigation are discussed presenting the wake vortex development and evolution in the near field and extended near field behind a four-engine large transport aircraft model fitted with a large winglet. The tests use a half-model of 1:32 scale focusing on the high-lift case of a typical approach configuration at a Reynolds number of 500,000 based on the wing mean aerodynamic chord and at an angle of attack of 7 deg. Flow-fields are carefully inspected by advanced hot-wire anemometry at seven crossflow planes up to 5.6 spans downstream of the model. Based on the measured time-dependent velocity components, the wake flow-field is analyzed by distributions of mean velocity and vorticity, turbulence intensities, and spectral densities. The near-field wing vortex sheet is dominated by seven main vortical structures, namely the winglet vortex, the

wing tip vortex, the outboard flap vortex, the outboard and inboard nacelle vortices, and the vortices shed at the wing-body junction and the horizontal tail plane. In the extended near field, these vortices roll up and merge to form the remaining rolled-up vortex. The deflection of winglet flaps produces additional vortices influencing the wing tip near field and enhancing the overall merging process. Especially for the cases with asymmetrical flap deflection, the remaining rolled-up vortex shows a significant narrowband concentration of turbulent kinetic energy which may result in an amplification of inherent far-field instabilities.

Allen, A. and Breitsamter, C.

"EXPERIMENTAL INVESTIGATION OF COUNTER-ROTATING FOUR VORTEX AIRCRAFT WAKE"

Aerospace Science and Technology, Vol. 13, 2009, pp. 114-129. [Also, 1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-181, September 2007, pp. 3413-3421.

An experimental investigation on the wake vortex formation and evolution of a four-vortex system of a generic model in the near field and extended near field as well as the behavior and decay in the far field region has been conducted by means of hot-wire anemometry in a wind tunnel. The results were obtained during an experimental campaign as part of the EC project FAR-Wake. The model used consists of a wing-tail plane configuration with the wing producing positive lift and the tail plane negative lift. The circulation ratio of tail to wing is -0.3 and the span ratio is 0.3. Thus, a four-vortex system with counter-rotating neighboring vortices exists. The model set-up was chosen on the condition to create a most promising four vortex system with respect to accelerate wake vortex decay by optimal perturbations enhancing inherent instability mechanisms. The flow field has been investigated up to a distance of 48 span dimensions downstream of the model and the results obtained at 1, 12, 24 and 48 span distances are shown as non-dimensional axial vorticity and vertical turbulence intensities. A significant decay in peak vorticity is observable during the downward motion of the vortices. Spectral analysis of the unsteady velocity data reveals a peak in the power spectral density distributions indicating the presence of a dominating instability. Cross spectral density distributions have also been extracted from the data gathered from two hot-wire probes, which highlight the co-operative instability leading to a rapid wake vortex decay within 30 span dimensions downstream.

Allen, C. B.

"PARALLEL SIMULATION OF LIFTING ROTOR WAKES IN FORWARD FLIGHT"

International Journal of Numerical Analysis and Modeling, Vol. 4, No. 1, 2007, pp. 1-15.

A finite-volume implicit, unsteady, multiblock, multigrid, upwind solver, and structured multiblock grid generator for rotors are presented, and applied to lifting rotors in forward flight. These flows are particularly expensive to compute as the accurate capture of the detailed vortical wake requires fine meshes away from the blades and, hence, a parallel version of the code has been developed allowing the use of very fine meshes. Parallel performance of the code is presented, and grid dependence of the computed blade loads and wake analyzed, by considering wake capturing, total blade load and

sectional load variation around the azimuth. It is demonstrated that the vortical wake capture is severely influenced by grid density, and even with 32 million points grid convergence is not approached. It is also shown that if blade loads only are of interest the vorticity dissipation is not a severe problem, and coarser meshes can be used. However, if more detail is required, for example blade-vortex interaction or aero-acoustic analysis, it would appear very difficult to capture the wake to any reasonable accuracy.

Allen, J. J. and Naitoh, T.

"EXPERIMENTAL STUDY OF THE PRODUCTION OF VORTEX RINGS USING A VARIABLE DIAMETER ORIFICE"

Physics of Fluids, Vol. 17, No. 6, June 2005, 061701-1-061701-4

A method for producing a vortex ring with an apparatus that utilizes a time varying aperture that closes during ring production is shown to have the capability for the production of rings of low nondimensional energy similar to a Hill's spherical vortex. This represents a difference of more than 50%, in terms of the nondimensional energy, of those which have been produced with fixed diameter generators. Experiments show that modulation of the rate at which the vortex ring generator produces kinetic energy, circulation, and impulse is the critical factor in determining what type of ring is formed.

Allen, K.

"AIRCRAFT WING TIP VORTEX TESTING METHODOLOGY, SIMULATION AND ANALYSIS TECHNIQUES"

AIAA Paper 2017-3888, June 2017, Denver, CO.

User requirements prompted new field testing procedures to collect and examine the behavior of wing tip vortices that are generated by large aircraft, such as the United States Air Force C-17 Globemaster III. This study describes the unique test methodology, rationale, and data analysis of wing tip vortices recorded in a series of flight tests that occurred at U.S. Army Yuma Proving Ground, AZ in April 2014. The study provides lessons learned, conclusions, and recommendations for future studies. Empirical wing tip vortex data was then used to perform an initial validation of a Vortex Modeling Tool to determine its accuracy in predicting actual wing tip vortex behavior. Although this study was performed in a personnel parachute airdrop environment, data and test techniques discussed have potential benefits in commercial passenger and cargo aircraft flight planning, which are also significantly affected by wing tip vortices.

Allerton, D. J., Spence, G. T.

"WAKE VORTEX ENCOUNTERS IN A FLIGHT SIMULATOR"

Aeronautical Journal, Vol. 114, No. 1159, September 2010, pp. 579-587.

A real-time model of a wake vortex has been developed for an engineering flight simulator, which enables studies to be undertaken into the effects of wake vortex encounters with civil transport aircraft. A brief summary of the methods used to create a vortex model and integrate it with a real-time flight simulator is presented. Tools have been developed to determine the structural loads on an aircraft during a simulated wake vortex encounter and to visualize the airframe loads. Four wake vortex encounters were flown with different pilot recovery strategies and automatic flight controls. It is clear from analysis of these results that it is difficult for a pilot to appreciate the margin of tail loading during an encounter and a prototype training display is outlined to enable pilots to fully understand the effects of rudder inputs in recovery from these events.

Allocco, M. A., Blair, J., Lintzenich, J., Nguyen, Q. A., Haltli, B. M. and Thomas, D. S. L.

"SAN FRANCISCO INTERNATIONAL AIRPORT SIMULTANEOUS OFFSET INSTRUMENT APPROACH CEILING REDUCTION TO 1600 FEET"

Report DOT-FAA-AFS-410-03, October 2011, FAA Flight Technologies and Procedures Division, Washington, DC.

As part of the Safety Management System process this Operational Safety Assessment was completed in conjunction with Technical Report DOT FAA-AFS-440-76; Evaluation to determine if pilots can develop a wake turbulence avoidance strategy while conducting Simultaneous Offset Instrument Approaches (SOIA) at San Francisco International Airport (SFO) with a ceiling of 1,600 feet. The conclusion of this assessment is that pilots are able to develop a wake turbulence avoidance strategy with a ceiling of 1,600 feet and no new mitigations are required.

Al-Mahadin, A. and Bouslama, F.

"AUTOMATIC IDENTIFICATION OF WAKE VORTEX TRAVERSE BY TRANSPORT AIRCRAFT USING FUZZY LOGIC"

4th International Conference on Soft Computing and Machine Intelligence, November 2017, Port Louis, Republic of Mauritius, pp. 133-139.

Aircraft trailing vortices result sometimes in significant disturbance to following aircraft. Separation standards between leading and following aircraft are sometimes over estimated, hence reducing airport capacity. An important contribution to the formation and revision of vortex separations lies in the recognition of wake vortex traverse by pilot reports together with a manual analysis of the flight data routinely recorded by flight data recorders (FDRs). This process has many disadvantages and, therefore, it is desirable to have an automatic identification technique, which can save time, and is both accurate and simple to implement. In this paper, fuzzy logic (FL) is used to model and identify vortex encounters. FL tolerates data imprecision and cope well with complexities in modeling the vortex encounters. Fuzzy linguistic variables are used to model FDR data. Fuzzy rules are derived from a collection of 54 pilot reports of vortex encounters and 210 flight records from FDRs. FL identification models are analyzed and the fuzzy rule base is optimized. An average success rate of identification of

83.7 percent is obtained. This automatic identification system should enable the aviation authorities to review regularly the appropriateness of wake vortex separation criteria to enhance safety and increase airport capacities.

Al-Mahadin, A. and Bouslama, F.

"NEURO-FUZZY TECHNIQUES FOR THE IDENTIFICATION OF AIRCRAFT WAKE VORTEX ENCOUNTERS"

Advances in Science, Engineering and Technology Conference (ASET 2018), February 2018, Dubai, UAE.

The automatic identification of aircraft vortex encounters by soft-computing techniques, such as fuzzy systems, gives better identification results than when performed by subjective manual approaches. However, the construction of the fuzzy rules heavily depends on a thorough understanding of vortex aerodynamics and aircraft response to a vortex encounter. Moreover, it requires a detailed analysis of flight data records and pilot reports, which all help in the proper selection of the critical fuzzy input variables. However, the automatic identification of vortex encounters by fuzzy logic can be greatly influenced by the shape and distributions of membership functions. Artificial neural networks integrated with fuzzy systems have been used as a solution in the automatic tuning of the membership functions of fuzzy linguistic variables. In this paper, a hybrid Adaptive Neuro-Fuzzy Inference System (ANFIS) is selected to automatically tune the parameters of the fuzzy membership functions. Various neuro-fuzzy models having different sets of parameters and factors are investigated. Simulation results with an average identification accuracy of 84.2 percent is obtained. The neuro-fuzzy hybrid model can also be used in the identification of other aircraft flight events such as wind shear and hard landing.

Al-Mahadin, A. and Dalkilic, S.

"INVESTIGATION OF FACTORS AFFECTING AIRCRAFT VORTEX ENCOUNTERS"

Advances in Science, Engineering and Technology Conference (ASET 2018), February 2018, Dubai, UAE.

Large aircraft wake vortices may sometimes cause significant disturbance to following aircraft. Separation standards between landing and following aircraft are proven to be overestimated in some cases, and therefore reducing airport capacity. Other times they are underestimated and hence causing aircraft incidences and accidents. An important contribution to the formation and revision of vortex separations depends on the recognition of vortex traverse by analysis of pilot reports together with a manual examination of data from flight data recorders (FDRs). However, the current process of flight events analysis is sometimes subjective and time consuming. Furthermore, there is sometimes disagreement between pilot reporting and analysis of flight data from FDR. Hence the current process requires improvement. This paper examines 54 pilot reports of transport aircraft vortex encounters to establish factors affecting the encounters. The research findings help the aviation authorities to impose new requirements such as training for pilots and FDR analysts on vortex identification. Findings can also contribute to enhance safety, improve operation efficiency and help revision of the appropriateness of regulations of vortex separations. This paper also indicates further investigation areas that are essential for aircraft wake vortex analysis, identification and severity mitigation.

Almgren, A. S., Buttke, T. and Colella, P.

"A FAST ADAPTIVE VORTEX METHOD IN THREE DIMENSIONS"

Journal of Computational Physics, Vol. 113, 1994, pp. 177-200

The method of local corrections (MLC) developed by Anderson for two spatial dimensions is a particle-particle particle-mesh method, in which the calculation of the velocity field induced by a collection of vortices is split into two parts: (i) a finite difference velocity field calculation using a fast Poisson solver, the results of which are used to represent the velocity field induced by vortices far from the evaluation point; and (ii) an N-body calculation to compute the velocity field at a vortex induced by nearby vortices. We present a fast vortex method for incompressible flow in three dimensions, based on the extension of the MLC algorithm from two to three spatial dimensions and the use of adaptive mesh refinement in the finite difference calculation of the MLC. Calculations with a vortex ring in three dimensions show that the break-even point between the MLC with AMR and the direct method is a N about 3000 on a Cray Y-MP; for N about 64,000 MLC with AMR can be 12 times faster than the direct method. Results from calculations of two colliding inviscid vortex rings demonstrate the increased resolution which can be obtained using fast methods.

Alonso, C. M.

"UAS SENSITIVITY TO WAKE TURBULENCE FOR ESTABLISHING SAFETY DISTANCE REQUIREMENTS"

MS Thesis, September 2014, Universitat Politècnica de Catalunya, Barcelona, Spain.

Nowadays, the aviation industry is one of the most important sectors in our society with a great variety of aircraft. Its development and evolution have brought the appearance of new aircraft and, consequently, an increase in the number of aircraft operations in both air and on the ground. Increasing the number of activities in both Air Traffic Management (ATM) and Air Traffic Flow Management (ATFM) has also led to a greater use of the airspace capacity. What it means is that the capacity has been optimized to perform more aircraft operations per minute without considering the aerial rules and regulations already established. One of the consequences of the optimization of the airspace capacity was the closer approximation between aircraft, or in other words, a reduction of the distance between the leading and the following aircraft. The approximation, which was carried out without considering any law, led to some dangerous situations between aircraft due to the appearance of an effect on the following aircraft, called turbulences or shaking effects, which had never experienced before and which led them to be crashed. Thus, scientists established an uncertainty area, called Wake Turbulence, which should be avoided by all aircraft flying behind another aircraft in order to prevent such dangerous situations. Consequently, the aim of this thesis is to understand what a wake turbulence is and to establish safety distances requirements between aircraft. On the one side, what it is going to be studied is what a wake turbulence is, including its properties and characteristics, for a better understanding of what it is. On the other side, a type of modeling of the wake turbulence done previously is going to be studied to know how much the wake turbulence descends and moves and, once it is done, a new modeling of the wake turbulence is going to be performed basing on

previous studies. In addition to it, another simulation is going to be performed to see some collision scenarios between aircraft where the wake turbulence is involved. And, finally, once it is done, the minimal safety distance that UAS will have to maintain respect to other aircraft may be estimated.

Aloysius, S. S. and Wrobel, L. C.

"ON THE USE OF NEAR FIELD COMPUTATIONAL FLUID DYNAMICS FOR IMPROVING AIRPORT RELATED DISPERSION MODELS"

3rd International Conference on Research in Air Transportation, June 2008, Fairfax, VA, pp. 413-420.

This paper discusses one of the major problems concerning current dispersion modelling techniques used around airports; the source dynamics characterization. Due to the lack of information and non-availability of experimental data, common dispersion models rely on very simple source approximations. Through a staged process, the paper shows a more accurate representation of the plume dynamics of an aircraft during the take-off phase. Using Computational Fluid Dynamics, useful data can be collected to represent and understand the fluid mechanics associated with the dispersion process. The results can help dispersion modelers with better source dynamics representation and benefit the management of aircraft time separation delays in the take-off and landing phases.

Aloysius, S. S. and Wrobel, L. C.

"LARGE EDDY SIMULATION OF PLUME DISPERSION BEHIND AN AIRCRAFT IN THE TAKE-OFF PHASE"

Environ. Fluid Mechanics, Vol. 9, 2009, pp. 457-470.

The aim of this paper is to provide an investigation, using large eddy simulation, into plume dispersion behind an aircraft in co-flowing take-off conditions. The complete geometry of a Boeing 737 is modelled and investigated. The current work represents a contribution towards a better understanding of the source dynamics behind an airplane jet engine during the take-off and landing phases. The information provided from these simulations will be useful for future improvements of existing dispersion models.

Aloysius, S. S., Pearce, D. and Wrobel, L. C.

"COMPARISON OF CFD AND LAGRANGIAN METHODS -- SIMPLE SCENARIO DURING TAKE-OFF"

EuroControl Report EEC/SEE/2007/001, 2007, Brunel University, Uxbridge, UK.

This report aims to simulate the dispersion of NO_x from an aircraft engine during the take-off phase, and to provide information on source dynamics for future improvements of existing dispersion models. The dispersion of a single engine, typical of the B-737, was simulated first, followed by the simulation of a twin engine. The results are discussed in detail and compared with results from other papers dealing with related problems, in order to correlate some of the findings. The method employed to characterize the plume dynamics employs state-of-the-art CFD software packages, which represent the

most advanced mathematics that can be applied to the simulation of fluid flow. The Large Eddy Simulation turbulence model was used to model the smaller eddies present within the grid resolution, and to solve explicitly the large eddies contained outside it. The conclusions from the report highlight the importance of two parameters, namely wind data and vortical structures, for both simulations. Another important parameter for the double engine simulation relates to the interaction effects between the two engines. The implication of the results will also be of benefit to air traffic management, for the efficient prediction of time separation delays between aircraft in the take-off and landing phases.

Al-Sakka, H., Weill, A., Le Gac, C., Ney, R. and Dupont, E.

"CURIE: A NEW CLEAR AIR DOPPLER RADAR DEDICATED TO THE LOWER PART OF THE ATMOSPHERIC BOUNDARY LAYER (20M - 750M)"

14th International Symposium for the Advancement of Boundary Layer Remote Sensing, IOP Conf. Series: Earth and Environmental Science, Vol. 1, 2008, pp. 012015-1 to 012015-7.

A new X-band mini-radar, CURIE radar (Canopy Urban Research on Interactions and Exchanges), mainly adapted to low Atmospheric Boundary Layer sounding has been developed at CETP. After a brief description of the opportunity and working conditions in a turbulent atmosphere, main characteristics are presented. Though this radar works in presence of precipitation as all X-band radar can do, this paper is more dedicated to clear air used in the turbulent atmospheric boundary layer. We are presented comparisons with UHF observations and boundary layer information which can be inferred from CURIE as entrainment across the inversion layer.

Alsayed, O. A., Asrar, W. and Omar, A. A.

"EVALUATION OF AIRCRAFT WING-TIP VORTEX USING PIV"

10th Asian International Conference on Fluid Machinery, CP 1225, AIP Conference Proceedings, Vol. 1225, 2010, pp. 382-390.

The formation and development of a wing-tip vortex in a near and extended near field were studied experimentally. Particle image velocimetry was used in a wind tunnel to measure the tip vortex velocity field and hence investigate the flow structure in a wake of aircraft half-wing model. The purpose of this investigation is to evaluate the main features of the lift generated vortices to find ways to alleviate hazardous wake vortex encounters for follower airplanes during start and approach such that the increase in airport capacity can be achieved. First the wake structure at successive downstream planes crosswise to the axis of the wake vortices was investigated by measuring parameters such as core radius, maximum tangential velocities, vorticities, and circulation distributions. The effect of different angles of attack setting on vortex parameters was examined at one downstream location. In very early stages the vortex sheet evolution makes the tip vortex to move inward and to the suction side of the wing. While the core radius and circulation distributions hardly vary with the downstream distance, noticeable differences for the same vortex parameters at different angles of

attack settings were observed. The center of the wing tip vortices scatter in a circle of radius nearly equal to 1% of the mean wing chord and wandering amplitudes shows no direct dependence on the vortex strength but linearly increase with the downstream distance.

Alsayed, O. A., Asrar, W., Omar, A. A., Kwon, K. and Jung, H.

"EXPERIMENTAL INVESTIGATION OF WING TIP VORTEX"

AIAA Paper 2009-1486, Jan. 2009, Orlando, FL

Particle image velocimetry was used in a low-speed wind tunnel to investigate and characterize wing tip vortex structures. A rectangular wing of a SWIM model was used as a vortex generator in two different configurations, (i) plain wing and (ii) flapped wing with trailing edge flap extended at 20 degrees. Vortex flow quantities and their dependence on angle of attack at a chord base Reynolds Number of 32800 and 43800 were evaluated. Assessment of measured data reveals that the peak values of tangential velocities, vortex strength and vorticities are directly proportional to the angle of attack. The vortex core radius value grows slowly as the angle of attack is increased. Both plain and flapped configurations showed similar trends. The peak tangential velocities and circulation distributions doubled when the flapped configuration was used instead of the plain wing.

Altaf, A., Omar, A. A., Asrar, W. and Jamaluddin, H. B. L.

"STUDY OF THE REVERSE DELTA WING"

Journal of Aircraft, Vol. 48, No. 1, January-February 2011, pp. 277-286.

Particle image velocimetry was used in a low-speed wind tunnel to investigate the vortex structure of a slender reverse delta wing at various angles of attack and roll. This work investigates the characteristics of the vortices generated downstream in planes perpendicular to the freestream direction and their dependence on angles of attack and roll at a chord-based Reynolds number of $Re = 382,000$. The peak tangential velocities at an angle of attack greater than 5 degrees show a trend like a delta wing. A six-component balance was used to obtain the aerodynamic coefficients for a reverse delta wing as well as a delta wing for comparison. A simulation of streamlines, velocity vectors, and surface pressure contours was carried out using computational fluid dynamics software to show the characteristics of the flow over a reverse delta wing.

Altaf, A., Thong, T. B., Omar, A. A. and Asrar, W.

"EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF A REVERSE DELTA TYPE ADD-ON DEVICE ON THE FLAP-TIP VORTEX OF A WING"

3rd International Conference on Mechanical, Automotive and Aerospace Engineering, in IPO Conf. Series: Materials Science and Engineering, Vol. 184, 2017, Kuala Lumpur, Malaysia, pp. 012002-1 to 012002-11.

Particle Image Velocimetry was used in a low-speed wind tunnel to investigate the effect of interactions of vortices produced by an outboard flap-tip of a half wing (NACA 23012 in landing condition) and a slender reverse delta type add-on device, placed in the proximity of the outboard flap-tip, on the upper surface of the half wing. This work investigates the characteristics of the vortex interactions generated downstream in planes perpendicular to the free stream direction at a chord-based Reynolds number of $Re = 274,000$. It was found that the add-on device significantly reduces the tangential velocity magnitude and enlarges the vortex core of the resultant vortex by up to 36.1% and 36.8%, respectively.

Altaf, A., Thong, T. B., Omar, A. A. and Asrar, W.

"INFLUENCE OF A REVERSE DELTA-TYPE ADD-ON DEVICE ON WAKE VORTEX ALLEVIATION"

AIAA Journal, Vol. 54, No. 2, February 2016, pp. 625-636.

Particle image velocimetry was used in a low-speed wind tunnel to investigate the effect of interactions of vortices produced by a wingtip of a half-span wing (NACA 23012 in landing condition) and a slender reverse delta-type add-on device placed near the tip on the upper surface of the half-span wing. This work investigates the characteristics of the vortex interactions generated downstream in planes perpendicular to the freestream direction and their dependence on angles of attack at a chord-based Reynolds number of $Re = 275,000$. It was found that the add-on device significantly reduced the tangential velocity, vorticity, and circulation magnitude by up to 82.9, 92.6, and 42.8 percent, respectively, and increased the resultant vortex core radius by a factor of 6.57. A six-component force balance was used to obtain the aerodynamic performance of the half-span wing model with a reverse delta-type add-on device. It was found that the reverse delta-type add-on device marginally affected the aerodynamic performance of the half-span high-lift configuration wing model.

Alter, K. W., Barrows, A. K., Jennings, C. W. and Powell, J. D.

"3-D PERSPECTIVE PRIMARY FLIGHT DISPLAYS FOR AIRCRAFT"

Proceedings of the IEA 2000/HFES 2000 Congress, July 2000, San Diego, CA, pp. 3-29 to 3-32.

Using a 3-D perspective display, Stanford University has flown numerous approaches and missed approaches. The system has been flown extensively on a Beechcraft Queen Air in the working air traffic environment. Inflight evaluations included tunnel approaches overlaid on existing non-precision procedures, curved and segmented approaches, traffic patterns flown by instrument reference, and skywriting with GPS. Augmentations to the perspective flight display, including perspective terrain and dynamic terrain alerting, are viable and improve pilots' situational awareness.

Alter-Gartenberg, R.

"STEREO-VIDEO DATA REDUCTION OF WAKE VORTICES AND TRAILING AIRCRAFTS"

NASA/CR-1998-208719, September 1998, Computer Sciences Corp., Hampton, VA

This report presents stereo image theory and the corresponding image processing software developed to analyze stereo imaging data acquired for the wake-vortex hazard flight experiment conducted at NASA Langley Research Center. In this experiment, a leading Lockheed C-130 was equipped with wing-tip smokers to visualize its wing vortices, while a trailing Boeing 737 flew into the wake vortices of the leading aircraft. A Rockwell OV-10A airplane, fitted with video cameras under its wings, flew at 400 to 1000 feet above and parallel to the wakes, and photographed the wake interception process for the purpose of determining the three-dimensional location of the trailing aircraft relative to the wake. The report establishes the image-processing tools developed to analyze the video flight-test data, identifies sources of potential inaccuracies, and assesses the quality of the resultant set of stereo data reduction.

Althaus, W. and Weimer, M.

"REVIEW OF THE AACHEN WORK ON VORTEX BREAKDOWN"

IUTAM Symposium on Dynamics of Slender Vortices, Aachen, Germany, August 31-September 3, 1997

Results of the numerical simulations and of the experimental investigations of vortex breakdown are presented. This paper focuses on the development of physical understanding of the breakdown process. Simulations of axisymmetric flows suggested that the Navier-Stokes equations for time-dependent, three-dimensional flows should be solved to describe the breakdown process. The simulation of a free vortex showed bubble- and spiral-type breakdown and the transition between these states. The comparison with the experimental visualization showed a good agreement, thus the analysis of the physical mechanisms of breakdown were based on the numerical results. The initiation and growth of the bubble are described by a feedback mechanism. The shedding of high axial velocity structures is explained. The growing asymmetry of the internal bubble structure and the subsequent transition to spiral-type breakdown are described. Simulating vortex breakdown in a slightly diverging tube showed stable bubble and further downstream spiral-type breakdown. The location and internal structure of the bubble corresponds to experimental results. The results of the application of flow visualizations and Particle-Image-Velocimetry are presented.

Althaus, W., Krause, E., Hofhaus, J. and Weimer, M.

"BUBBLE- AND SPIRAL-TYPE BREAKDOWN OF SLENDER VORTICES"

Experimental Thermal and Fluid Science, Vol. 11, 1005, pp. 276-284.

Bubble- and spiral-type breakdown and periodic transition between the two were visualized by varying the volume flux in a transparent, low-speed, vertical water tunnel with a diffuser inset. A feedback model for the initiation and development of bubble-type breakdown is proposed, and the transition from bubble- to spiral-type breakdown is explained by an asymmetry of the circumferential vorticity distribution. Both are qualitatively confirmed by experimental flow visualization. The initiation of the bubble-type breakdown and its transition to the spiral-type were successfully simulated by

solving the Navier-Stokes equations for three-dimensional, unsteady, and incompressible flow with boundary conditions similar to those of an experimental investigation. Hence, for the first time it was possible to compare the results of numerical and experimental flow visualizations and therefore to draw a conclusion about the reliability of simulating vortex breakdown numerically.

Altman, A.

"DESIGN METHODOLOGY FOR LOW SPEED HIGH ALTITUDE LONG ENDURANCE UNMANNED AERIAL VEHICLES"

21st International Council of the Aeronautical Sciences Congress ICAS, September 1998, Melbourne, Australia.

High Altitude Long Endurance (HALE) Unmanned Aerial Vehicles (UAV's) are increasingly being considered to perform a wide range of tasks. Recent years have seen greater value of UAV's in the military reconnaissance arena, first in the Persian Gulf war, with the use of small UAVs, and more recently over Bosnia with medium sized UAVs.

Alvarez, E. J. and Ning, A.

"DEVELOPMENT OF A VORTEX PARTICLE CODE FOR THE MODELING OF WAKE INTERACTION IN DISTRIBUTED PROPULSION"

AIAA Paper 2018-3646, June 2018, Atlanta, GA.

Recent developments in electric aircraft technology have enabled the use of distributed propulsion for the next generation of vertical lift vehicles. However, the ability to rapidly assess the performance of these design concepts, with sufficient fidelity, is a current weakness of this nascent industry. This paper explores the capacity of the viscous Vortex Particle Method (VPM) to model wake interactions found in distributed propulsion. The elements of the vortex particle method are summarized, and a new approach for the calculation of vortex stretching through the complex-step derivative approximation is presented. Preliminary validation is performed on vortex ring cases resembling the fundamental dynamics encountered in propeller wakes. Unsteady wake dynamics of individual propellers are successfully modeled, replicating the instabilities that lead to vortex breakdown as observed experimentally. Comparing the method with results from momentum theory, it is shown that VPM is consistent with theoretical values of near and far field induced velocities, and a notable feature is its ability to model near/far field transition. Furthermore, VPM is able to fully characterize induced velocities across the entire wake, from the stable region where momentum theory operates, through instability transition and eventual vortex breakdown. The simulation of a multirotor configuration of two tip-to-tip propellers is shown, displaying the capacity of VPM to model wake mixing. The results presented here are intermediate steps in the development of a mid-fidelity modeling tool for the early design stages of distributed-propulsion electric aircraft.

Amelsberg, S.

"THE CREDOS PROJECT: PILOT MODEL FOR WAKE VORTEX ENCOUNTER SIMULATIONS FOR TAKE-OFF AND DEPARTURE"

CREDOS Report D3-6, November 2009.

A pilot model (PM) is developed for fast-time Monte Carlo Simulations with varying wake vortex encounter conditions for safety analyses. The model consists of different submodules to perform the take-off run, rotate, follow a standard instrument departure route and recover and stabilize the aircraft during and after a wake vortex encounter. The PM generates sidestick pitch, sidestick roll, pedal, throttle lever, flap lever, and landing gear lever commands and manipulates those control elements as a pilot would do. For design and validation of the PM, data was generated in a certified A330 Full Flight Simulator and on A320 development simulator with licensed commercial airline pilots. For final validation, the PM was implemented into the flight simulation to compare it with recorded pilot reactions.

Amelsberg, S.

"WAKE VORTEX ENCOUNTER SEVERITY CRITERIA FOR TAKE-OFF AND DEPARTURE"

CREDOS Report D3-5, November 2009, Technical University of Berlin, Berlin, Germany.

Criteria shall be identified that quantify the severity of a Wake Vortex Encounter during takeoff and departure. This paper describes the development process of suitable metrics that can estimate the hazard of a wake vortex encounter situation based on objective aircraft state parameters. It is applicable for Monte Carlo simulation and suitable for risk assessments. The hazard estimation based on the identified criteria is verified with the hazard ratings of human pilots. The reference data were gathered during piloted simulator tests.

Amelsberg, S.

"TRAJECTORY MODELS FOR TAKEOFF AND DEPARTURE"

CREDOS Report D3-1, September 2007, Technical University of Berlin, Berlin, Germany.

The European Commission funded CREDOS (Cross wind reduced separations for departure operations) project aims to demonstrate the validity of reducing departure separations under conditions of sufficient crosswind. For this validation a safety assessment is required, which will be performed by Monte Carlo Simulation (MCS) of aircraft departure trajectories. This paper describes the development of an aircraft trajectory model, which is a part of the MCS. The requirement to generate trajectories for different kind of aircraft can be fulfilled by a simple point mass model (3DoF) consisting of three main parts: (i) A database of all relevant aircraft parameters, nominal departure route information, meteorological conditions, (ii) pilot model, (iii) and the description of the aircraft behavior with the equations of motion. The simulated flight path is subdivided into the following segments

which describe the different kinds of flight phases: lift-off, unsteady climb, steady climb, acceleration, and transitions between these phases.

Amelsberg, S.

"ADDENDUM FOR TRAJECTORY MODELS FOR TAKE-OFF AND DEPARTURE"

CREDOS Report D3-1, November 2007, Technical University of Berlin, Berlin, Germany.

This addendum documents the validation of the Boeing 737-300, Airbus 300-600, and the Airbus 340-300. It is an addition to Appendix A of the deliverable D3-1.

Amelsberg, S. and Kauertz, S.

"PILOTED WAKE VORTEX ENCOUNTER SIMULATOR TESTS FOR DEPARTURE"

CREDOS Report D3-4, November 2008, Technical University of Berlin, Berlin, Germany.

Piloted simulator tests were carried out to study and assess the safety hazard imposed by wake vortices during departures. The tests were conducted in Hamburg at the A320 THOR simulator and in Berlin at the A330 full-flight simulator with several rated airline pilots. On one hand, objective parameters of the pilot's response in wake vortex encounter conditions and resulting aircraft reactions were recorded and on the other hand the pilots subjective ratings of the encounter severity were documented. The hazard rating scale ranges from slight aircraft upsets with no pilot reaction required up to extreme disturbances with temporary loss of control. Test planning, accomplishment and the first steps of parameter correlation are discussed.

Amelsberg, S. and Luckner, R.

"PARAMETRIC AIRCRAFT TRAJECTORY MODEL FOR TAKEOFF AND DEPARTURE"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-273, September 2007, pp. 785-795

The European Commission funded CREDOS (Cross wind reduced separations for departure operations) project aims to demonstrate the validity of reducing departure separations under conditions of sufficient crosswind. For this validation a safety assessment is required that computes encounter probabilities and encounter severity by means of Monte Carlo Simulation (MCS). This paper describes the development of an aircraft trajectory model for departure of vortex generating and following aircraft. This model is a part of the MCS. The requirement to generate trajectories for different aircraft types can be fulfilled by a simple point mass model consisting of three main parts: (i) a database of all relevant aircraft parameters, nominal departure route information, meteorological conditions, (ii) pilot model, and (iii) the description of the aircraft dynamic by the equations of motion. The simulated flight path is subdivided into segments that are described by the following flight phases: lift-off, unsteady climb, steady climb, acceleration, and transitions between these phases. Finally,

results of a deterministic model validation based on high-fidelity flight simulation for a specific aircraft as well as the model validation based on aircraft trajectories measured at Frankfurt airport are presented.

Amromin, E.

"ANALYSIS OF VORTEX CORE IN STEADY TURBULENT FLOW"

Physics of Fluids, Vol. 19, 2007, pp. 118108-1 to 118108-3.

Profiles of velocity and pressure for the vortex core in turbulent flow were obtained by solving Reynolds equation for the circumferential component of the fluid momentum. The viscous core radius is defined as a function of viscosity coefficient, vortex intensity, and a Reynolds stress component. The obtained velocity profiles are in much better agreement with known experimental data than are the Rankin vortex profiles.

An, R., Kontis, K. and Edwards, J. A.

"COMPRESSIBLE VORTEX-RING INTERACTION STUDIES WITH A NUMBER OF GENERIC BODY CONFIGURATIONS"

AIAA Paper No. 2005-1044, Reno, NV, January 2005

An experimental study has been conducted to examine compressible vortex ring structure and propagation, and the interaction of vortex ring with generic-body configurations. The experiments used a circular 30mm internal diameter and 38mm outer diameter shock-tube. The driver and driven gas was air. A vortex ring was generated by the impulse of the shock wave emerging from the open end of the shock-tube. High-speed schlieren photography was employed. Both side view and 45 degrees oblique photographs were taken. The interactions with generic shape objects, which were a circular cone, a sphere, a cube, and a plane-wall, were studied. Three different driver pressures of 12, 8, and 4 bars were tested with driven gas at 1 bar; the shock wave Mach number inside the tube was 1.63, 1.52 and 1.25 respectively.

Anand, G. and Graham, W. R.

"VORTEX FILAMENT SIMULATION OF TRAILING VORTEX MERGER"

AIAA Paper No. 2005-4854, Toronto, Canada, June 2005

Aircraft in high-lift configuration shed multiple vortices. These generally merge to form a downstream wake consisting of two counter-rotating vortices of equal strength. The understanding of the merger of two co-rotating trailing vortices is important in evaluating the separation criteria for different aircraft to prevent wake vortex hazards during landing and take-off. There is no existing theoretical method on the basis of which such norms can be set. The present study is aimed at gaining a better understanding of the behavior of wake vortices behind the aircraft. Two dimensional studies are carried out using the

vortex blob method and compared with Bertenyi's experiment. It is shown that inviscid two-dimensional effects are insufficient to explain the observations. Three dimensional studies, using the vortex filament method, are applied to the same test case. Two Lamb-Oseen profile vortices of the same dimensions and initial separation as the experiment are allowed to evolve from a straight starting condition until a converged steady flow is achieved. The results obtained show good agreement with the experimental distance to merger. Core radius and separation behavior is qualitatively like experiment, except for rapid increases at first. This may be partially attributable to the choice of filament-element length, and recommended further work includes a convergence study for this parameter.

Ananthakrishnan, P. and Yeung, R. W.

"NONLINEAR INTERACTION OF A VORTEX PAIR WITH CLEAN AND SURFACTANT-COVERED FREE SURFACES"

Wave Motion, Vol. 19, 1994, pp. 343-365.

Two-dimensional unsteady viscous-flow problem associated with the normal incidence of a counter-rotating vortex pair on a free surface is analyzed. Effects of surface tension and insoluble surfactants on the generation of free-surface vorticity and surface waves are investigated. A recently developed finite-difference method based on boundary-fitted coordinates is used to solve the fully-nonlinear problem. Results show that in the absence of surfactants and at low Froude number (based on circulation strength and initial separation distance of the vortex pair), waves of short lengths are generated. However, secondary vorticity generated in this case is not strong enough to affect the outward translation of the primary vortices. At intermediate Froude number, a transient wave developing outboard of the primary vortex becomes steep, and eventually breaks because of local instability. Consequently, free-surface vorticity inhibits the outward translation of the primary vortices. Surface tension in a clean free surface dampens the steep short waves, hence also the generation of free-surface vorticity. However, variation in surface tension induced by surfactants intensifies the generation of surface vorticity, thereby causing the primary vortices to rebound. The increase in the rotational part of wave motion results in the dampening of overall free-surface deformations. However, it is found that the shear stress associated with a large gradient of surfactant concentration could cause local steepening of the short-wave generated outboard of the primary vortex.

Ananthan, S.

"ANALYSIS OF ROTOR WAKE AERODYNAMICS DURING MANEUVERING FLIGHT USING A FREE-VORTEX WAKE METHODOLOGY"

PhD Thesis, 2006, University of Maryland, College Park, MD.

The problem of helicopter rotor wake aerodynamics during maneuvering flight conditions was analyzed using a time-accurate, free-vortex wake methodology. The free-vortex method consists of a Lagrangian representation of the rotor flow field using vortex elements, where the evolution of the

flow field is simulated by tracking the free motion of these vortex elements and calculating their induced velocity field. Traditionally, free-vortex methods are inviscid, incompressible models, but in the present approach the viscous effects are incorporated using a viscous splitting method where the viscous and inviscid terms are modeled as successive sub-processes. The rotor aerodynamics and rigid blade flapping dynamics are closely coupled with the wake model and solved for in a consistent manner using the same numerical scheme. Validations of the methodology with experimental data were performed to study the wake response to perturbations in collective and cyclic pitch inputs. The numerical simulations captured all the essential wake dynamics observed in flow visualization. The predictions of the transient inflow and air loads response were found to be in excellent agreement with the available experimental measurements. It was observed that the rotor wake was extremely sensitive to perturbations in collective and cyclic blade pitch inputs. The characteristic wake response was found to be the bundling of the wake vorticity into a vortex ring structure. The evolution, convection and subsequent breakdown of this bundled ring of tip-vortices was found to be highly nonlinear, and occurs with a temporal lag. The nonlinear induced velocity field associated with unsteady wake evolution can cause considerable fluctuations in the rotor air loads time-history if the bundled tip-vortex structure comes near the rotor blades.

Ananthan, S. and Leishman, J. G.

"TRANSIENT HELICOPTER ROTOR WAKES IN RESPONSE TO TIME-DEPENDENT BLADE PITCH INPUTS"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1025-1041

A time-accurate, free-vortex method was used to predict the evolution of a helicopter rotor wake and the corresponding unsteady rotor air loads in response to time-varying changes in blade pitch. Both steady and maneuvering flight conditions were examined. The modeling was validated using measured rotor responses to transient increases in collective pitch and also for oscillatory collective and cyclic blade pitch inputs. In each case the results showed that there was a temporal lag in the growth and convection of vorticity into the rotor wake, causing significant unsteady effects at the rotor. For transient blade pitch inputs, the calculated results showed the bundling of individual vortex filaments below the rotor into vortex rings, a result also verified experimentally. These vortex rings, however, subsequently break down through the development of Kelvin waves. A simulated piloted pull-up maneuver from descending flight was studied, producing evidence that maneuvers can also cause wake vorticity to bundle below the rotor. Large unsteady rotor air loads were produced as the blades encountered this accumulated wake vorticity. A study was also conducted to examine the effects of small-amplitude, low-frequency blade pitch inputs, typical of pilot control inputs during flight. Overall, it is apparent that even moderate control inputs can have a significant impact on the temporal developments of the rotor wake.

Ananthan, S., Leishman, J. G. and Ramasamy, M.

"THE ROLE OF FILAMENT STRETCHING IN THE FREE-VORTEX MODELING OF ROTOR WAKES"

58th Annual Forum and Technology Display of the American Helicopter Society International, Montreal, Canada, June 2002

The problem of filament strain or flow field 'stretching' effects are discussed within the context of time-marching, free-vortex filament modeling of rotor wakes. It is shown that for most practical rotor flight conditions, wake distortions create velocity fields that impose three-dimensional strain on the vortex filaments, stretching these filaments, and changing their vorticity and induced velocity field. Such strain or stretching effects are not easily neglected without proper justification. The basic approach used here to model these effects, applies a Prandtl-type decomposition of the inviscid and viscous contributions into successive sub-processes, with a recombinant solution to give a consistent level of approximation to the rotor wake problem. A parsimonious model based on an equivalent diffusion time is developed to account for and couple the effects of filament straining into the viscous part of the solution. Examples of wake predictions are shown for rotors operating in hover, forward flight, flight near the ground, and during descending flight. It is shown that even for benign flight conditions, strain effects on vortex filaments can be significant, and including the effects of strain on the viscous characterization of the vortices is important for predictions of the rotor wake development.

Anderson, C. R., Chen, Y.-C. and Gibson, J. S.

"CONTROL AND IDENTIFICATION OF VORTEX WAKES"

Transactions of the ASME, Vol. 122, June 2000, pp. 298-305

In this paper, control and identification methods for vortex wakes are investigated. The problem studied concerns the stabilization of vortices behind a flat plate, using backside suction as an actuator. The flow dynamics are modeled with a discrete vortex method. Feedback control results for a linear PI controller are presented as well as identification results for a class of input/output models that can be used to design more sophisticated controllers.

Anderson, E. A. and Lawton, T. A.

"CORRELATION BETWEEN VORTEX STRENGTH AND AXIAL VELOCITY IN A TRAILING VORTEX"

Journal of Aircraft, Vol. 40, No. 4, July-August 2003, pp. 699-704

The vortices that trail from the wingtips of a large aircraft provide a significant hazard to an aircraft that follows in its wake. The objective is to contribute to the understanding of these vortices by identifying the conditions where an axial velocity in excess of the freestream value will be generated in the core of a trailing vortex. The axial velocity near the core of a trailing vortex was measured using a triple-sensor hot-wire probe and compared with measured values of vortex circulation strength. The vortex was generated in a wind tunnel using a NACA 0015 wing model with a semispan aspect ratio of 0.80. A linear relationship between the axial velocity and a nondimensional circulation parameter is indicated. For small values of the circulation parameter, the axial velocity shows a velocity deficit. An increase in circulation strength results in a progressive increase in axial velocity, which can exceed the freestream velocity by as much as 70%. The results indicate that the magnitude of the axial velocity is

sensitive to the two end-cap configurations, flat and rounded, that were tested. It was found that scaling the circulation parameter by the vortex radius collapses the data from both configurations to a single linear curve.

Anderson, E. A. and Lawton, T. A.

"EFFECT OF WING LOADING ON AXIAL VELOCITY IN A WINGTIP VORTEX"

AIAA Paper No. 2001-0578, Reno, NV, January 2001

Theories pertaining to the cause of an axial velocity excess in a free trailing vortex are evaluated and compared to experimental measurements. It was found that several previous analyses contain an inconsistency that leads to the conclusion that an axial velocity excess will occur in the core of a line vortex. In the current study 3-component hot-wire velocity measurements were used to calculate the circulation strength in a trailing vortex generated by a NACA 0015 wing. The results were compared to the measured axial velocity near the center of the vortex. A strong correlation between wing loading as defined by a non-dimensional circulation parameter and the axial velocity was determined. For low circulation parameter values, below approximately 0.1, the axial velocity was less than the freestream value or 'wake-like'. For larger parameter values the axial velocity exceeded the freestream resulting in 'jet-like' behavior. A linear relationship between circulation strength and axial velocity was found. It is concluded that the cause of the velocity excess is streamwise directed downwash.

Anderson, E. A., Wright, C. T. and Lawton, T. A.

"EXPERIMENTAL STUDY OF THE STRUCTURE OF THE WINGTIP VORTEX"

AIAA Paper No. 2000-0269, Reno, NV, January 2000

The development of a wingtip vortex in the region adjacent the wing end-cap to approximately two chord lengths downstream from the trailing edge is strongly influenced by Reynolds number, angle-of-attack, and end-cap treatment. This study primarily focuses on the role of wing end-cap geometry on the initial development of the tip vortex and how that development is altered by angle-of-attack. The velocity field in the vicinity of the end-cap of a NACA 0015 wing section was measured using a triple-sensor hot wire probe and compared to flow visualization results. The results indicate that a 'jet-like' axial velocity profile will be generated for loading parameter values of the order 0.2 while much lower loading will produce a 'wake-like' profile. In addition, the flat end-cap geometry produced multiple, relatively strong vortices in the near-field as opposed to the single vortex generated using the rounded end-cap configuration. These different structures influenced the downstream development of the wingtip vortex.

Anderson, M. R., Miake-Lye, R. C., Brown, R. C. and Kolb, C. E.

"CALCULATION OF EXHAUST PLUME STRUCTURE AND EMISSIONS OF THE ER 2 AIRCRAFT IN THE STRATOSPHERE"

Journal of Geophysical Research, Vol. 101, No. D2, February 1996, pp. 4025-4032.

Calculations are presented for the NASA ER 2 aircraft at high altitude to simulate measurements taken of its own emissions during a wake-crossing event. Results are presented for a Mach = 0.71 case in the lower stratosphere with an engine NO_x emission index of 4.6 corresponding to the measured value. A series of codes was used in the analysis to calculate the flow field and chemical kinetics, from the engine combustor out to a distance of about 20.2 km (97 s). Initial plume properties were calculated with a two-dimensional computational fluid dynamics code with finite rate chemistry. The results of the plume code initialized a three-dimensional parabolized Navier-Stokes reacting flow solution, where the plume dynamics interacting with the aircraft wake were calculated out to the region of plume breakup. Results show that the early shape and mixing rate of the engine exhaust plume are dominated by the presence of the aircraft vortex wake. Model results for NO_x emissions compare well to in situ measurements taken in the field. Calculated exhaust species evolutions predict several species ratios in good agreement with field data. The mixing rate of the engine plume was also predicted to be consistent with dilution measured in the field.

Anderson, M. R., Miaki-Lye, R. C., Brown, R. C. and Kolb, C. E.

"NUMERICAL MODELING OF REACTING ENGINE PLUMES AND AIRCRAFT WAKE INTERACTIONS"

AIAA Paper No. 1996-0948, Reno, NV, January 1996

The effects of aircraft emissions on the chemical balance of the atmosphere has gained increasing attention in recent years. New generations of higher speed aircraft which would fly up into the stratosphere have been a particular concern. A host of experimental and analytical efforts to quantify these effects is being pursued through NASA's Atmospheric Effects of Aviation Program as well as other international efforts. Proper numerical analysis of the reacting near field region of the engine plume(s) presents several challenges. Chemical models must be constructed which are valid in the atmospheric temperature and pressure range and must include the relevant nitrogen, carbon, and sulfur species. In addition, flow field modeling is complicated by the interaction which occurs between the engine plume and the aircraft wake vortices which roll off the wings. This phenomenon substantially affects the mixing and dilution of the plume. Results are presented here for several aircraft of various designs, speeds, and altitudes. The analysis consists of a Parabolized Navier-Stokes CFD approach coupled with a specially developed finite rate chemistry model. The focus will be on the external near field region from the exit plane of the engine to the point of wake breakup several kilometers downstream. Comparisons of analytical results to field data are shown for the ER-2, Boeing 747, and Concorde aircraft.

Ando, T. and Haraguchi, E.

"MOBILE COHERENT DOPPLER LIDAR SYSTEM FOR WIND SENSING"

17th Coherent Lidar Conference, June 2013, Barcelona, Spain.

We have developed ultra compact all-fiber Coherent Doppler LIDAR (CDL) system for wind sensing, called Man-pack LIDAR. The dimension of the Man-pack LIDAR is 40x30x16.5 cm, its weight is 13.9 kg and its power consumption is only 46.7 W. Thanks to low power consumption optical transmitter/receiver unit, this new CDL system can be operated by two Lithium polymer batteries, and it can continue to measure over two hours without exchanging batteries. This Man-pack LIDAR has also successfully marked the maximum range for wind velocities more than 1 km as long as our conventional all-fiber CDL product.

Andreopoulos, Y., Xanthos, S. and Agui, J.

"VORTICITY DYNAMICS IN INTERACTIONS OF SHOCK OR EXPANSION WAVES WITH TURBULENCE AND VORTICES"

AIAA Paper No. 2006-706, Reno, NV, January 2006

The interaction of planar shock waves or expansion waves with homogeneous and isotropic turbulence and induced longitudinal and spanwise vortices generated by a wing have been investigated experimentally in the CCNY Shock Tube Research Facility at several Reynolds numbers. A custom made hot-wire vorticity probe was designed and developed capable of measuring the time-dependent highly fluctuating three-dimensional velocity and vorticity vectors, and associated total temperature, in non-isothermal and inhomogeneous flows with reasonable spatial and temporal resolution. These measurements allowed the computations of the vorticity stretching/tilting terms, vorticity generation through dilatation terms, full dissipation rate of kinetic energy term and full rate-of-strain tensor. These results indicate that the outcome of the interaction depends strongly on the upstream turbulence of the flow.

Andreotti, B., Maurer, J., Couder, Y. and Douady, S.

"EXPERIMENTAL INVESTIGATION OF TURBULENCE NEAR A LARGE SCALE VORTEX"

European Journal of Mechanics, B/Fluids, Vol. 17, No. 4, 1998, pp. 451-470.

The influence of a strong large-scale vortex on neighboring turbulence is investigated. For this purpose, the statistical properties of the tangential velocity fluctuations are systematically investigated as a function of the distance to the vortex core. Far from the vortex, the characteristics usually found in isotropic homogeneous turbulence are approximately obtained. In the central region of the vortex a strong decrease of the amplitude of the velocity fluctuations and of the dissipation is observed. However, in this region of space the flow is not smooth: the energy spectrum $E(k)$ still exhibits the equivalent of an inertial range but with a slope which can range from k to -1.25 power to k to -1 power instead of the classical k to $-5/3$ power. Furthermore, the intermittence is much weaker inside the vortex central region: the velocity differences PDFs no longer exhibit long stretched tails and are more self-similar from scale to scale. In between these two regions, at the periphery of the vortex, the intermittence is strongly increased. It is shown that this increase is due to the mixing in the velocity signal of the two types of statistics (the strongly fluctuating bulk turbulence and the weakly fluctuating

vortex flow). This situation is analyzed using a variant of extended self-similarity that we call LSS (loose self-similarity) which lends itself to the analysis of situations where a clear scaling is not obvious.

Andrews, D. R.

"A FLIGHT INVESTIGATION OF THE WAKE BEHIND A METEOR AIRCRAFT, WITH SOME THEORETICAL ANALYSIS"

A.R.C. Current Paper 282, December 1954, Royal Aircraft Establishment, Farnborough, England.

An experimental investigation of the wake behind a Meteor-4 aircraft has been carried out, and theory used wherever possible to confirm and extend the results obtained. Tests with a Vampire flying in the wake of the Meteor show that the strength of the vortices fall to about one-half its initial value by 8000 feet behind the aircraft. Theory and flight test experience showed that the rolling moment imposed on a tracking aircraft constituted the most serious disturbance from the vortices.

Andrews, W. H.

"FLIGHT EVALUATION OF THE WING VORTEX WAKE GENERATED BY LARGE JET TRANSPORTS"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 287-288

A flight program has been conducted to update the current knowledge relative to the behavior of wing wake vortices generated by existing large transport aircraft and future jumbo jet transports. The tests were conducted to evaluate the wake location, persistence, apparent intensity and influence out of ground effect and primarily under terminal area configuration and operational conditions. Test aircraft included a DC-9, CV-990, and a C-5A. The wake behavior was evaluated by measuring aircraft response and controllability of a series of probe airplanes flying in the generating aircraft wake at separation ranges of 1 to 15 nautical miles.

Andrews, W. H., Drinkwater, F. J., Krier, G. E. and Robinson, G. H.

"FLIGHT-TEST EVALUATION OF THE WING VORTEX WAKE GENERATED BY LARGE JET-TRANSPORT AIRCRAFT"

FAA Compilation of Working Papers Concerning Wake Turbulence Tests, April 1970.

An evaluation of the behavior of the wing vortex wake of large, jet transport airplanes is presented. The primary objectives of the test program were to provide preliminary information to establish a logical terminal-area airspace separation criterion for all types of aircraft operating in the proximity of large transports. The flight tests were conducted to obtain data for the determination of the wing vortex wake location, persistence, and intensity behind the generating airplanes. In addition, a portion of the testing was directed toward evaluating the effects of the wing vortex wake on several different classes of aircraft.

Andrews, W. H., Robinson, G. H. and Larson, R. R.

"AIRCRAFT RESPONSE TO THE WING TRAILING VORTICES GENERATED BY LARGE JET TRANSPORTS"

NASA Aircraft Safety and Operating Problems, NASA SP-270, Vol. 1, 1971, pp. 115-126

The paper summarizes the NASA effort to evaluate the effect of the wing-tip vortex wake generated by large jet transport airplanes on a variety of smaller airplanes. The investigation was designed to obtain data essential to the determination of the wing-wake location relative to the generating aircraft and the apparent strength and dissipation of the vortex at a specified point along the wake trail. An additional objective was to evaluate the upset potential and subsequent recovery capability of a variety of airplanes penetrating the vortex system.

Andrews, W. H., Robinson, G. H. and Larson, R. R.

"EXPLORATORY FLIGHT INVESTIGATION OF AIRCRAFT RESPONSE TO THE WING VORTEX WAKE GENERATED BY JET TRANSPORT AIRCRAFT"

NASA TN D-6655, March 1972, NASA Flight Research Center, Edwards, CA

The effect of intercepting wing tip vortices generated by large jet transports, including jumbo jets, over separation distances from 1 nautical mile to 15 nautical miles is evaluated based on the response of a vortex probe airplane in the roll mode. The vortex probe test aircraft included a representative general aviation airplane, an executive jet, a fighter, and light and medium weight jet transports. The test conditions and airplane configurations were comparable to those normally used during takeoff, landing, or holding pattern operations. For flight safety the tests were performed at altitudes from 9500 feet to 12,500 feet. In addition to an evaluation of the probe airplane response, a flight test technique is suggested for determining minimum separation distance, using as variables the ratio of vortex-induced roll acceleration to maximum lateral control acceleration and the gross weight of the generating aircraft.

Andrews, W. H., Tymczyszyn, J. J., Jacobsen, R. A. and Drinkwater, F. J.

"FLIGHT INVESTIGATION OF THE RESPONSE OF WIDE-BODY TRI-JET TO THE WING VORTEX WAKE GENERATED BY LARGE TRANSPORT AIRCRAFT"

FWP-35, February 1973, NASA Flight Research Center, Edwards, CA

A flight test program was conducted which included a Lockheed C-5A and a McDonnell Douglas DC-10-40 airplane as the vortex wake generating airplanes. The vortex wake probe airplanes consisted of a DC-10-10, a DC-9-10, L-1011, and a Learjet-23. The data analysis was based on the probe airplane roll response resulting from the wake vortex of the generating airplane and the corresponding probe airplane lateral power available to oppose the induced vortex rolling moment.

Angelucci, S. B.

"A MULTIVORTEX METHOD FOR AXISYMMETRIC BODIES AT ANGLE OF ATTACK"

Journal of Aircraft, Vol. 8, No. 12, December 1971, pp. 959-966

A multi-vortex model made up of many discrete free vortices has been used to represent the actual vortex sheets shed from the lee side of a slender body at an angle of attack. Circulation, strength, and position of the vortices, together with the induced normal forces, are evaluated at various axial positions along the body axis. The viscous inputs to the analysis are the separation or feeding points which are provided by experiment or semi-empirical theories. A discussion of the numerical computations and a comparison with experimental data are presented.

Anmin, Q.

"NUMERICAL STUDY OF WAVE PROPAGATION ON VORTEX FILAMENTS"

Journal of Computational Physics, Vol. 104, 1993, pp. 185-210

Simulations of a vortex tube in unbounded, inviscid, incompressible fluid flow using three-dimensional vortex filament methods are presented. The numerical parameters that determine accuracy are investigated. Methods to deal with the truncated ends, which arise in the simulation of a part of a vortex tube, are developed. The non-monotonic response of the vortex filament evolution using the vortex method to variation of core size is observed. The effect of a small torsion of a wave on vortex stretching is discussed. The long-time propagation of a periodic wave of constant helical shape along a vortex tube is illustrated.

Anon.

"WAKE TURBULENCE EVENT, SYDNEY AIRPORT, NSW, 3 NOVEMBER 2008"

Australian Transport Safety Report, Investigation AO-2008-077, November 2009.

On 3 November 2008, a SAAB Aircraft Company 340B-229, registered VX-ORX, was conducting a regular public transport flight from Orange, NSW to Sydney. The crew reported that at about 0724 Eastern Daylight-saving Time, when tracking to join a 7 NM (13 km) final for runway 34 Right (34R), a passenger sustained minor injuries following a possible wake turbulence event that resulted in a momentary loss of control of the aircraft. Examination of the available radar, meteorological and aircraft operational data identified that the momentary upset probably resulted from wake turbulence, which was generated by an Airbus Industrie A380-800 (A380) that was conducting a parallel approach to runway 34 Left (34L). There was a 35 kt left crosswind affecting both aircraft's approaches.

Anon.

"STANDARDS DEVELOPMENT ACTIVITIES FOR USING NEAR REAL-TIME AIRCRAFT-DERIVED DATA IN FUTURE APPLICATIONS"

DO-360, RTCA, September 2015, RTCA, Washington, DC.

The Wake Vortex Tiger Team (WVTT) accomplished an extensive review of the current state of wake vortex research along with an assessment of current and planned wake vortex mitigation applications. Extensive domestic and international participation on the WVTT contributed to broad support of the Findings and Recommendations. In addition, the WVTT considered the needs of Air Traffic Management and weather applications, all of which will benefit from a rich environment of near real-time reporting from aircraft. The WVTT attempted to lay out a logical framework of Findings and Recommendations which can be acted upon, and believe there is much opportunity to improve the safety and efficiency of air traffic management systems in the future by incorporating more frequent and near real-time weather reports from aircraft.

Anon.

"AVIATION INVESTIGATION REPORT: ENCOUNTER WITH WAKE TURBULENCE, AIR CANADA, A319-114, C-GBHZ, WASHINGTON STATE, UNITED STATES"

Report A08W0007, 2008, Transportation Safety Board of Canada, Ontario, Canada.

On 10 January 2008, the Air Canada Airbus A319-114 (registration C-GBHZ, serial number 0813), operating as flight ACA190, was en route from Victoria International Airport, British Columbia, to Toronto Lester B. Pearson International Airport, Ontario on a regularly scheduled flight with 83 passengers and 5 crew members on board. The aircraft was at flight level (FL) 350 and following a United Airlines Boeing 747-400, flight UAL896, in level cruise at FL 370 over the state of Washington, United States (U.S.). When separation had increased to 8.1 nautical miles (nm), with UAL896 in the lead, U.S. air traffic control cleared ACA190 to climb from FL 350 to its flight planned altitude of FL 370. At 0648 Pacific standard time, as ACA190 was climbing through FL 366, 10.7 nm behind UAL896, sharp jolts were felt in ACA190, followed by a series of rolls. During the roll oscillations, the aircraft continued the climb to FL 369 and then descended to FL 355, where the crew regained straight and level flight. The crew declared an emergency and diverted the flight to Calgary International Airport, Alberta where it landed uneventfully at 0728. Eight passengers and crew received minor injuries and three received serious injuries due to falls and collisions with aircraft furnishings.

Anon.

"GLOBAL IMPLEMENTATION OF RVSM NEARS COMPLETION"

Flight Safety Digest, Vol. 23, No. 10, October 2004, pp. 1-21.

Reduced vertical separation minimum (RVSM) for aircraft being flown at 29,000 feet through 41,000 feet has been applied in many regions; North America, South America and the Caribbean will follow in

January 2005. Experience has shown that increased traffic congestion below RVSM airspace and wake-turbulence encounters in RVSM airspace have not been significant problems.

Anon.

"FAA REPORT ON AIRPORT CAPACITY, VOLUME II - EIGHT AIRPORT SURVEY"

FAA-EM-74-5, II, January 1974, FAA Office of Systems Engineering, Washington, DC.

This study analyzes the impact of FAA programs on airport capacity over the next ten years. The results are reported in two volumes. The first volume forms a summary of the findings of the study; the second volume presents the detailed examinations of each of the selected airports. Eight major airports (Atlanta, Chicago O'Hare, Denver, Los Angeles, Miami, New York Kennedy, Philadelphia, and San Francisco) were examined in detail. The study found that these programs will have substantial benefits at the airports surveyed. VFR capacities will increase about 25 percent over today, and IFR about 50 percent. A major requirement will be the metering and spacing and wake vortex avoidance systems programs. With these systems in place, IFR capacity will rise from its present level of 75 percent of VFR capacity to about 90 percent, thus increasing the ability to maintain sustained all-weather operations. If these improvements are achieved, no airport surveyed will in the long term (1979-82) experience peak hour VFR saturation, and only one airport is projected to experience peak hour IFR saturation.

Anon.

"ENVIRONMENTAL FACTORS AFFECTING LOSS OF CONTROL IN-FLIGHT: BEST PRACTICE FOR THREAT RECOGNITION AND MANAGEMENT"

Report, International Air Transport Association, 2016, Montreal, Quebec, Canada.

In the IATA 2015 Safety Report, less than one tenth of accidents in the period 2011-2015 were categorized as Loss of Control (LOC-I) but approaching a half of all fatal accidents in the period were found to be LOC-I. Environmental threats were identified in a significant proportion of all LOC-I accidents and therefore a strong link can be drawn between environmental factors and fatal accidents. IATA has prepared this guidance material to bring together industry knowledge and identified best practices in a single document. For the purposes of the document the environmental factors to be considered are meteorological phenomena such as convective weather and the associated conditions, turbulence in clear air and turbulence from aircraft wake vortices.

Anon.

"AN INTEGRATED ATMOSPHERIC DATABASE FOR THE IDAHO FALLS VORTEX EXPERIMENTS OF 23-30 SEPTEMBER 1990"

Project Report, June 1994, System Resources Corporation, Burlington, MA.

The purpose of this paper is to describe and document an atmospheric dataset for the Idaho Falls wake vortex field tests that integrates the data from the 200-foot met tower with the tether sonde data into gridded height vs. time cross-sections that have eliminated most noise signals while retaining most meso-scale features. The source data, analysis approach, and resulting gridded datasets are described.

Anon.

"TECHNICAL SUPPORT PACKAGE FOR LAR-14568 OFF-SURFACE FLOW VISUALIZATION USING SULFUR HEXAFLUORIDE GAS AND INFRARED IMAGING"

NASA Langley research Center, TSP LAR-14568, 1993.

A new off surface flow visualization technique that consists of seeding the vortex (or other off-surface flow phenomenon) with a gas that has a strong infrared absorbing/emitting characteristic and then visualizing the flow with an IR imaging system is described. The example highlighted involves using sulfur hexafluoride gas entrained into a wing tip vortex. This gas has a strong absorption/emission characteristic in the 8 to 12 micrometer range, and therefore an IR imager of the same wavelength range is used to visualize the flow. The technique was illustrated on a NASA P-28 research aircraft.

Anon.

"GUIDELINES FOR IN SITU EDDY DISSIPATION RATE (EDR) ALGORITHM PERFORMANCE"

DO-370, RTCA, December 2017, RTCA, Washington, DC.

This document defines the minimum user performance requirements applicable to in situ Eddy Dissipation Rate (EDR) turbulence computational algorithms (hereafter referred to as 'the EDR algorithm'). In situ, as used herein, refers to calculations that use aircraft derived observations, obtained through direct contact with the atmosphere or aircraft, as input (as opposed to remote sensing observations, such as RADio Detection And Ranging (RADAR) or LIght Detection And Ranging (LIDAR)).

Anon.

"A3XX - THE MARKET WILL DECIDE"

Aircraft Technology Engineering & Maintenance, No. 39, April-May 1999, pp. 16-18, 21, 22

This article discusses the issues surrounding the postponed Airbus Industrie's A3XX very large aircraft program. The article examines how Airbus Industrie intends to clear the economic and technical hurdles facing the aircraft prior to its planned commercial launch in 2000. Specifically, the topics of fragmentation and consolidation, program developments, technical hurdles, the wake vortex produced by the large aircraft, airport compatibility, and the business aspects are discussed.

Anon.

"NTSB URGES GREATER SEPARATION FOR SOME AIRCRAFT BEHIND B-757's"

ITSA Report, Vol. 1, No. 1, March 1994

Greater separation distances have been recommended by the U.S. NTSB for following Boeing 757 s. This was precipitated by a series of accidents involving planes following B-757's on landing approaches. These accidents were caused by wake vortices. The new separation distances are greatest for very small aircraft and smallest for aircraft nearing the weight of 757's. The NTSB also called for: better and more established air traffic control procedures and information for pilots of B-757 and similar weight aircraft on proper flight path guidance during landing approaches; prohibition of visual approach clearances for IFR aircraft landing behind larger airplanes in the large or heavy category until the airplane is in-trail and the closure rate is such that the pilot can maintain the minimum IFR separation without excessive maneuvering; issuance of information by controllers to VFR landing aircraft about wake turbulence, name of aircraft manufacturer and model, separation distance, and other data relevant to wake turbulence avoidance; and expanded training and information for controllers and pilots about the wake vortex problem and avoidance procedures.

Anon.

"LASER RADAR SCANS THE SKY"

Design Engineering, July/August 1997, pp. 17-18.

Discusses the use of laser radar in the study and monitoring of the wake vortex produced by an aircraft. The research work about vortices by DERA/Malvern at Heathrow Airport is described.

Anon.

"AVOIDING WAKE TURBULENCE"

Flight Deck, Issue 31, Spring 1999, pp. 40-45.

The FAA has issued a 'Wake Turbulence Training Aid' manual. This training resource was developed to reduce the number of wake turbulence accidents and incidence. The newly revised data and procedures should be useful to pilots.

Anon.

"PLANNING OF ARMY AVIATION FACILITIES"

Technical Manual 5-803-4, March 1979, Department of the Army, Washington, DC

This manual presents the general provisions, criteria, and policy for guidance in planning, designing, and construction programming of permanent U.S. Army airfields, heliports, and related facilities.

Anon.

"TECHNICAL CONFERENCE ON THE EFFECTS OF HELICOPTER DOWNWASH ON FREE PROJECTILES"

U.S. Army Aviation Systems Command, St. Louis, MO, November 1975

Proceedings of a conference on the effects of helicopter downwash on free projectiles. A chronological bibliography on rotor downwash from 1922 to 1975 is included.

Anon.

"LONDON CITY AIRPORT WAKE TURBULENCE STUDY"

Final Report, December 2010, Halcrow Group Limited, London, England.

The purpose of this study is to satisfy obligations in the Agreement which accompanies the planning permission granted by the London Borough of Newham (LBN) on 9 July for an increase in permitted annual aircraft movements to 120,000. The planning agreement requires London City Airport to submit a Wake Turbulence Study to LBN. The purpose of the study is to investigate any damage arising to buildings around the Airport because of wake turbulence, together with recommendations to address each damage or the risk of such damage and procedures that should be adopted to handle any claims for compensation arising from such damage. Because damage has only been reported at one location near the Airport the assessment of risk must be based on a combination of empirical research and experience from airports with a record of turbulence damage. The sensitivity of the issue makes access to data on vortex damage incidence at other airports difficult. Studies have therefore had to rely on sources in the public domain, including industry and academic research, public inquiry evidence, and airport publications such as consultative committee minutes.

Anon.

"WAKE VORTEX CAPACITY BENEFITS FOR SIMULTANEOUS APPROACHES AT ST. LOUIS AIRPORT"

FTA-TM-506-1, June 1994, Flight Transportation Associates, Inc., Cambridge, MA

This paper details the results of FTA's investigation into the potential capacity gains of applying 1.5 nautical mile (NM) diagonal separation between parallel arrival operations at St. Louis Lambert International Airport (STL). Currently, dependent parallel arrivals are permitted only when runways are separated by 2,500 feet or more due to concern over wake vortex turbulence. If conditions exist which eliminate or reduce this effect, the application of diagonal separation may be permitted between runways separated by less than 2,500 feet. A similar study was completed for Boston's Logan International Airport and much of the material in this memorandum reflects the previous Logan analysis. The way the runways are used is dependent upon several factors including weather, traffic demand, and the type of aircraft operation (e.g. jet versus propeller). Information on STL operations was obtained from the STL Tower and the Air Traffic Division of the FAA Central Region Office.

Anon.

"WAKE VORTEX LIDAR SYSTEM REPORT AND DOCUMENTATION: THE AVOSS DEMONSTRATION AT DALLAS/FORT WORTH INTERNATIONAL AIRPORT JUNE-JULY 2000"

RTI/7473/1002-03, Research Triangle Institute, Raleigh-Durham, N. C., October 2000

In response to the reduced spacing operations element of the NASA Terminal Area Productivity program, the Wake Vortex Lidar (WVL) at NASA Langley Research Center (LaRC) has developed and extensively field-tested an experimental 2-micron 100 Hertz ground-based pulsed coherent lidar system for aircraft wake vortex and turbulence detection. The goal of the project is to provide wake vortex and atmospheric wind measurement support to the Aircraft Vortex Spacing System (AVOSS). The WVL Project developed a detection system that supported the wake vortex detection and weather measurement functions of AVOSS.

Anon.

"VORTEX RESEARCH BUILDS"

Jane's Airport Review, Vol. 6, No. 7, September 1994, pp. 60-61

The National Aeronautics and Space Administration (NASA), in conjunction with the FAA, is conducting an aggressive wake vortex research program related to the Terminal Area Productivity Program. According to the director of the NASA program, the purpose is to increase airport capacity by accurately predicting safe separation distances using real-time data of atmospheric conditions and data specific to the airplane model.

Anon.

"RUSSIANS HELP CANADA PREDICT WAKE TURBULENCE"

Aviation Week & Space Technology, Vol. 140, No. 6, 7 February 1974, p. 24

Transport Canada is working with a Russian institute to perfect computer software designed to predict where wake turbulence vortices will move on an airfield. The objective of the project is to shift a Russian developed computer model onto western digital computers to see if a real-time predictive system could be developed for certification and use at airports.

Anon.

"WAKE TURBULENCE TRAINING PROGRAMME IS DESIGNED TO EDUCATE BOTH PILOTS AND AIR TRAFFIC CONTROLLERS"

Boeing Aero, December 1995, pp. 23, 29

A Boeing-led team, under the sponsorship of the Air Transport Association of America (ATA) and in conjunction with the U.S. Department of Transportation, completed development of the industry's most authoritative and extensive wake turbulence training aid in April 1995. Designed to educate both pilots and air traffic controllers, the informative training aid focuses on procedures that can help in avoiding encounters with wake turbulence.

Anon.

"DOCUMENTATION FOR THREE WAKE VORTEX MODEL DATA SETS FROM SIMULATION OF FLIGHT 587 WAKE VORTEX ENCOUNTER ACCIDENT CASE"

RTI/8438/006/-02F, January 2003, RTI International, Research Triangle Park, NC.

This document contains a general description for data sets of a wake vortex system in a turbulent environment. The turbulence and thermal stratification of the environment are representative of the conditions on November 12, 2001 near John F. Kennedy International Airport. The simulation assumes no ambient winds. The full three-dimensional simulation of the wake vortex system from a Boeing 747 predicts vortex circulation levels at 80 percent of their initial value at the time of the proposed vortex encounter. The linked vortex oval orientation showed no twisting, and the oval elevations at the widest point were about 20 meters higher than where the vortex pair joined. Fred Proctor of NASA's Langley Research Center presented the results of this work at the NTSB public hearing that started 29 October 2002. This document contains a description of each data set including: variables, coordinate system, data format, and sample plots. Also included are instructions on how to read the data.

Anon.

"IN-FLIGHT SEPARATION OF VERTICAL STABILIZER, AMERICAN AIRLINES FLIGHT 587 AIRBUS INDUSTRIE A300-605R, N14053, BELLE HARBOR, NEW YORK, NOVEMBER 12, 2001"

NTSB/AAR-04-04, 2004, National Transportation Safety Board, Washington, DC.

This report explains the accident involving American Airlines flight 587, an Airbus Industrie A300-605R, N14053, which crashed into a residential area of Belle Harbor, New York, following the in-flight separation of the airplane's vertical stabilizer and rudder. The safety issues discussed in this report focus on characteristics of the A300-600 rudder control system design, A300-600 rudder pedal inputs at high airspeeds, aircraft-pilot coupling, flight operations at or below an airplane's design maneuvering speed, and upset recovery training programs. Safety recommendations concerning these issues are addressed to the Federal Aviation Administration and the Direction General de l'Aviation Civile.

Anon.

"WAKE VORTEX MINIMIZATION"

NASA SP-409, 1977, NASA Headquarters, Washington, DC

The purpose of this conference is to present a status report on research directed at reducing the disturbances to the air behind aircraft as they fly through the atmosphere. The objective of such a reduction is to minimize the hazard to smaller aircraft that might encounter these wakes. The general guidelines given this research are that natural atmospheric motions be assumed negligible so that the alleviation schemes will be effective on calm days when the wakes are believed to be most persistent. A further restriction is that the alleviation is to be achieved by aerodynamic means, hopefully to be accomplished by changes on the wake-generating aircraft that are easy to retrofit onto existing aircraft.

Anon.

"ENGINEERING AND DEVELOPMENT PROGRAM PLAN - WAKE VORTEX"

FAA-ED-21-1A, 1977, FAA, Washington, DC

This Engineering and Development Program Plan defines the current research efforts investigating the wake vortex phenomenon. The overall objectives of the program are the design, development, testing, and prototyping of a system(s) to increase runway capacity by minimizing wake vortex effects as an impediment to efficient and effective traffic management in the terminal environment. The plan identifies and discusses the three major work areas: Vortex Advisory System, Wake Vortex Avoidance System, and Vortex Alleviation Research. Prior developments and related research are reviewed and future research requirements identified.

Anon.

"AIRCRAFT ACCIDENT REPORT - AIR PENNSYLVANIA 501, PIPER PA-31-350, N5MS, PHILADELPHIA, PENNSYLVANIA, JULY 25, 1980"

NTSB AAR-81-1, January 1981, NTSB, Washington, DC

On July 25, 1980, at 0713, Air Pennsylvania 501, a Piper PA-31-350 Navajo aircraft, crashed while making a visual approach to runway 27R at Philadelphia International Airport, Pennsylvania. The aircraft, a scheduled commuter flight from Reading, Pennsylvania, arrived in the Philadelphia Approach Control area as a VFR 'pop-up' flight and was sequenced to land behind United Flight 555, a Boeing 727 IFR arrival, on runway 27R. Witnesses stated that, when Flight 501 was about 1/2 mile on final approach, it rolled from side to side, pitched up, rolled inverted to the left, and flew into the ground nose first. All three persons aboard the aircraft were killed and the aircraft was destroyed. The National Transportation Safety Board determines that the probable cause of the accident was the loss of aircraft control due to an encounter with wake turbulence from the preceding aircraft at an altitude too low for recovery and the pilot's failure to follow established separation and flightpath selection procedures for wake turbulence avoidance.

Anon.

"SAFETY ISSUES RELATED TO WAKE VORTEX ENCOUNTERS DURING VISUAL APPROACH TO LANDING"

NTSB/SIR-94-01, February 1994, NTSB, Washington, D.C

The Safety Board conducted a special investigation to examine in detail the circumstances surrounding five recent accidents and incidents in which an airplane on approach to landing encountered the wake vortex of a preceding Boeing 757. Thirteen occupants died in two of the accidents. The encounters, which occurred during visual conditions, were severe enough to create an unrecoverable loss of control for a Cessna Citation, a Cessna 182, and an Israel Aircraft Industries Westwind. Additionally, there were significant but recoverable losses of control for a McDonnell Douglas MD-88 and Boeing 737 (both required immediate and aggressive flight control deflections by their flight crews). The safety issues discussed in this special investigation report are: the adequacy of the current aircraft weight classification scheme to establish separation criteria to avoid wake vortex encounters, the adequacy of air traffic control procedures related to visual approaches and visual flight rules operations behind heavier airplanes, pilot knowledge related to the avoidance of wake vortices, and the lack of available data to analyze the history of wake vortex encounters in the United States. Recommendations concerning these issues were made to the Federal Aviation Administration.

Anon.

"BOEING 757 WAKE TURBULENCE: A REVIEW OF THE ACTIONS OF THE FEDERAL AVIATION ADMINISTRATION"

DOT Office of the Secretary of Transportation, July 1994

On June 10, 1994, Secretary of Transportation Federico Pena and FAA Administrator David Hinton directed a review of the FAA's actions regarding wake turbulence associated with the Boeing 757. This was in response to public concern regarding the timeliness of the agency's actions in this area over the past several years. This was not a technical review of wake vortex research, air traffic control procedures, National Transportation Safety Board recommendations, or B757 wake vortices. The review instead focused on responses to issues raised by the B757 wake vortex and on the decision-making processes used by the agency in dealing with these issues.

Anon.

"WAKE TURBULENCE TRAINING AID"

DOT/FAA/RD-95/6, April 1995, DOT Volpe National Transportation Systems Center, Cambridge, MA

The goal of the Wake Turbulence Training Aid is to reduce the number of wake turbulence related accidents and incidents by improving the pilot's and air traffic controller's decision making and situational awareness through increased and shared understanding and heightened awareness of the factors involved in wake turbulence. The major three objectives of the Wake Turbulence Training Aid are: (1) to educate pilots and air traffic controllers on wake turbulence and avoidance of the phenomenon; (2) to increase the wake-turbulence situational awareness of pilots and air traffic controllers; and (3) to provide usable information to develop a ground training program.

Anon.

"VORTEX WAKE TURBULENCE - FLIGHT TESTS CONDUCTED DURING 1970"

FAA-FS-71-1, February 1971, FAA/NASA/Boeing Task Force, Washington, DC

The summary report covers the 1970 flight test program conducted by the Federal Aviation Administration in joint participation with the National Aeronautics and Space Administration and the Boeing Company. The objective was to update the interim air traffic separation standards issued on 21 January 1970 restricting the airspace behind the B-747 and C-5A aircraft. Flight tests were conducted at three locations: At Edwards Air Force Base, a CV-990 and F-104 probed the vortices of a C-5A. At Seattle, a B-707 and B-737 and F-86 probed the vortices of a B-747. In addition, approach, landing, takeoff, and crossing runway tests were conducted with a B-737 trailing a B-747. At Idaho Falls, aircraft were flown past an instrumented tower to obtain measurements of vortex core diameters and tangential velocities.

Anon.

"FAA SYMPOSIUM ON TURBULENCE"

Federal Aviation Administration, Washington, DC, March 1971

The Federal Aviation Administration sponsored Symposium on Turbulence was conducted in Washington, DC, 22-24 March 1971. Subjects covered at the Symposium included wake turbulence, clear air turbulence, wind shear, upsets, thunderstorms, and turbulence plotting.

Anon.

"A LASER-TELESCOPE SYSTEM TO ENHANCE AIRPORT SAFETY"

Optical Spectra, September 1971, p. 12

A pulsed argon laser with two reflecting telescopes is being used to develop techniques for measuring the velocities of vortices generated by jet aircraft. Preliminary results indicate the feasibility of applying the newly developed doppler shift technique to airport use.

Anon.

"ENGINEERING AND DEVELOPMENT PROGRAM PLAN: AIRCRAFT WAKE VORTEX AVOIDANCE SYSTEM"

FAA-ED-21-1, February 1973, Federal Aviation Administration, Washington, DC

Efforts to develop a Wake Vortex Avoidance System (WVAS) are discussed. The basic objective of the program is the design of a system to increase runway capacity by removing the capacity-restrictive

large spacings now required between aircraft to avoid wake vortex hazards. These large spacings will be replaced by separations tailored to aircraft type and prevailing meteorological conditions. In addition, by using vortex sensors, safety will be increased in the terminal area by warning of the existence of vortices in the aircraft approach and departure paths. The program consists of three major task areas: sensor development, vortex behavior, and hazard definition. These tasks will be integrated into an overall system design. Although the program will require up to five years to complete, interim capabilities specifically directed toward safety will be available in useable form in advance of the completion date.

Anon.

"AIR VORTEX WAKES AND THEIR CAUSE"

NASA-TT-F-14288, June 1972, Scientific Translation Service, Santa Barbara, CA

The dangers of air vortex wakes caused by jumbo jets such as the B-747 to air traffic are discussed. The effects of these wakes on other aircraft is described and safety measures are presented.

Anon.

"VORTEX HAZARD INDEX"

FAA Compilation of Working Papers Concerning Wake Turbulence Tests, April 1970

Equations are proposed for determining the vortex hazard index for the encountering aircraft. Equations are developed for calculating the vortex strength when the aerodynamic and inertia characteristics of the probe aircraft are known. It is concluded that further data is required to clarify the effect of the span of the encountering aircraft.

Anon.

"SYMPOSIUM ON AIRCRAFT WAKE TURBULENCE"

D1-82-0993, September 1970, Boeing Scientific Research Labs., Seattle, WA

Session topics: Fundamental problems; experimental methods; flow visualization, presentations, and results; wake formation and character; stability and decay of trailing vortices; aircraft response to wake turbulence; and control and use of trailing vortices.

Anon.

"AIRCRAFT ACCIDENT REPORT: DELTA AIR LINES, INC., MCDONNELL DOUGLAS DC-9-14 N3305L, GREATER SOUTHWEST INTERNATIONAL AIRPORT, FORT WORTH, TEXAS, 30 May 1972"

NTSB-AAR-73-3, March 1973, NTSB, Washington, DC

The crash of a DC-9 aircraft at Fort Worth, Texas airport on 30 May 1972 is reported. The crash occurred during an attempted go-around following a landing approach. The landing approach was normal, but the aircraft began oscillating after passing the runway threshold and finally struck the runway in an extreme right wing low attitude. It was determined that the cause of the accident was an encounter with a trailing vortex generated by a large jet aircraft which preceded the DC-9 to the runway.

Anon.

"SUBSONIC LIFT-DEPENDENT DRAG DUE TO THE TRAILING VORTEX WAKE FOR WINGS WITHOUT CAMBER OR TWIST"

ESDU-AERO-W.02.01.02, October 1974, Engineering Science Data Unit, London, England

A numerical expression for the lift-dependent drag coefficient due to the wing trailing vortex wake at subsonic speeds is derived. The data apply to unencumbered untwisted wings with straight leading and trailing edges and streamwise tips. The theory from which the data were obtained is linearized and relates to inviscid flow. Additional mathematical relationships are developed for wings with different planforms. Graphs of the drag coefficient for various wing shapes and airspeed conditions are provided.

Anon.

"VORTEX WAKES OF LARGE AIRCRAFT"

American Institute of Aeronautics and Astronautics, New York, NY, 1974

The aircraft trailing vortex problem is examined along with the behavior of vortex systems, rapid scanning three-dimensional hot-wire anemometer surveys of wing-tip vortices, axial flow in trailing line vortices, stability theory for a pair of trailing vortices, and studies of the stability of a vortex pair. Other subjects considered are related to flight test studies of the formation and dissipation of trailing vortices, aircraft wake dissipation by sinusoidal instability and vortex breakdowns, observations of atmospheric effects on vortex wake behavior, the decay of an isolated vortex, and the relationship between eddy transport and second-order closure models for stratified media and for vortices.

Anon.

"BIG PLANE TURBULENCE CAN CAUSE A FLIGHT HAZARD"

Safety Suggestions, No. 8, 1952, Beech Aircraft Corp., Wichita, KS.

A collection of pilot reports discussing experience pilots may have had in encountering turbulence in landing behind large aircraft. The reports comment on: what causes the hazard, what type of airplanes do the vortices affect, and what types of planes are reported to have caused the turbulence.

Anon.

"A PRELIMINARY STUDY OF THE EFFECT OF JET BLAST OR WAKE ON OTHER AIRCRAFT"

Beech Aircraft Corp., Wichita, KS, July 1955

This is a summary report of an industry survey of available technical information of the potential hazards of encountering the blast and/or wake of a preceding or passing jet aircraft and similar propeller-driven aircraft.

Anon.

"COMPILATION OF WORKING PAPERS CONCERNING WAKE TURBULENCE TESTS"

Federal Aviation Administration, Washington, DC, April 1970

The compilation contains four papers: (1) Flight-Test Evaluation of the Wing Vortex Wake Generated by Large Jet-Transport Aircraft by Andrews, Robinson, Krier and Drinkwater of NASA; (2) Results of the Boeing Company Wake Turbulence Test Program by Condit of Boeing; (3) Measurements of the Vortex Wake Characteristics of the Boeing 747, Lockheed C-5A, and Other Aircraft, data report by Garodz of DOT; and (4) Vortex Hazard Index.

Anon.

"WAKE TURBULENCE IS DANGEROUS"

Aviation Safety Digest Publication, Dept. of Civil Aviation, Melbourne, Australia, 1970

The hazards posed by wing tip vortices of large aircraft to light aircraft taking off or landing are discussed. Examples and illustrations of the phenomena are given. Flight rules are suggested for light aircraft to prevent accidents. These rules include: avoidance of flight below and behind large aircraft on takeoff, starting the takeoff run from the end of the runway to be airborne before the point where heavy aircraft have lifted off, and maintaining an above and beyond position during final landing approach. Air traffic control procedures are also discussed.

Anon.

"AIR VORTEX WAKES AND THEIR CAUSE"

Verband Deutscher Flugleiter E. V., 1971

The dangers of air vortex wakes caused by jumbo jets such as the B-747 to air traffic are discussed. The effects of these wakes on other aircraft is described and safety measures are presented.

Anon.

"AIRCRAFT WAKE TURBULENCE"

FAA Advisory Circular No. 90-23E, October 1991

The Advisory Circular alerts pilots to the hazards of aircraft trailing vortex and wake turbulence, and recommends related operational procedures.

Anon.

"VORTEX PROBE FLIGHT TEST (B-767 AIRCRAFT)"

Wake Vortex Research Data Package No. FAA/ACD-1, Feb. 1991, FAA Technical Center, Atlantic City Int'l Airport, NJ.

This document contains the processed data from probe testing of wake vortices of a Boeing 767 aircraft conducted during a 1990 fall series of flight tests. These tests were held at the NOAA test facility located near Idaho Falls, Idaho; also shown are the flight paths used for the test aircraft. Described herein are the aircraft and equipment used, in addition to the techniques for data collection and analysis. A representative set of data is also provided consisting of probe aircraft data, both instrumented (data collection and video) and knee-pad and chase aircraft data (video). Although no flow visualization was available for the testing, several vortex encounters were experienced by the probe aircraft, one of which was considered significant and is the subject of this data package.

Antkowiak, A. and Brancher, P.

"TRANSIENT ENERGY GROWTH FOR THE LAMB-OSEEN VORTEX"

Physics of Fluids, Vol. 16, No. 1, January 2004, pp. L1-L4

The transient evolution of infinitesimal flow disturbances which optimally induce algebraic growth in the Lamb-Oseen (Gaussian) vortex is studied using a direct-adjoint technique. This optimal perturbation analysis reveals that the Lamb-Oseen vortex allows for intense amplification of kinetic energy for two-dimensional and three-dimensional perturbations of azimuthal wavenumber $m = 1$. In both cases, the disturbances experiencing the most growth initially take the form of concentrated spirals at the outer periphery of the vortex which rapidly excite bending waves within the vortex core. In the limit of large wavelengths, the optimal perturbation leads to arbitrarily large growths via an original scenario combining the Orr mechanism with vortex induction.

Antkowiak, A. and Brancher, P.

"ON VORTEX RINGS AROUND VORTICES: AN OPTIMAL MECHANISM"

J. Fluid Mech., Vol. 578, 2007, pp. 295-304

Stable columnar vortices subject to hydrodynamic noise (e.g. turbulence) present recurrent behaviors, such as the systematic development of vortex rings at the periphery of the vortex core. This phenomenon lacks a comprehensive explanation, partly because it is not associated with an instability *stricto sensu*. The aim of the present paper is to identify the physical mechanism triggering this intrinsic feature of vortices using an optimal perturbation analysis as a tool of investigation. We find that the generation of vortex rings is linked to the intense and rapid amplification of specific disturbances in the form of azimuthal velocity streaks that eventually evolve into azimuthal vorticity rolls generated by the rotational part of the local Coriolis force. This evolution thus appears to follow a scenario opposite to the classical lift-up view, where rolls give rise to streaks.

Antonov, V. A., Baranov, A. S. and Kondrat'ev, B. P.

"LOCAL VORTICES IN A DIFFERENTIALLY ROTATING FLOW"

Fluid Dynamics, Vol. 40, No. 1, 2005, pp. 71-82.

A time-dependent local elliptic vortex in a differential two-dimensional incompressible fluid flow is considered. Nonlinear oscillations of vortices of the cyclonic and anticyclonic types are described. It is found that the evolutionary tracks can be both closed and unclosed. The former corresponds to the azimuthal oscillations of the principal axis and the latter to the complete rotational state of the elliptic vortex. Steady-state solutions are also obtained; they are represented by ellipses elongated or compressed along the flow. Small oscillations of the vortex equilibrium figures are investigated and a general dispersion relation for arbitrary perturbations is derived. The stability criterion is found.

Anusonti-Inthra, P. and Floros, M.

"COUPLED CFD AND PARTICLE VORTEX TRANSPORT METHOD: WING PERFORMANCE AND WAKE VALIDATIONS"

AIAA Paper 2008-4177, June 2008, Seattle, WA

The development of a new hybrid CFD approach using fully coupled Reynolds-Averaged Navier-Stokes (RANS) and Particle-based Vorticity Transport Method (PVTM) solvers is summarized in this paper. The methodology is applied to predict the performance and wake parameters of an isolated wing in low-speed flow condition. The approach divides the flow field into several regions and uses appropriate flow solvers according to the dominant physical features of the flow in each region. The near body flow field, which is dominated by the effect of viscosity and geometry, is resolved using a 3D compressible RANS solver. The flow field outside of the RANS regions, which is primarily dominated by the vortices being shed from aerodynamic surfaces, is simulated using a viscous implementation of the PVTM method. The results obtained using the coupled RANS/PVTM analysis compare well with experimental

data, in particular the pressure distribution, sectional load, and tip vortex parameters (swirl velocity, core location, and core size).

Aono, H., Shyy, W. and Liu, H.

"NEAR WAKE VORTEX DYNAMICS OF A HOVERING HAWKMOTH"

Acta Mechanica Sinica, Vol. 25, No. 1, 2009, pp 23-36.

Investigation of vortex dynamics in near wake of a hovering hawkmoth and hovering aerodynamics is conducted to support the development of a biology-inspired dynamic flight simulator for flapping wing-based micro air vehicles. Realistic wing-body morphologies and kinematics are adopted in the numerical simulations. The computed results show 3D mechanisms of vortical flow structures in hawkmoth-like hovering. A horseshoe-shaped primary vortex is observed to wrap around each wing during the early down- and upstroke; the horseshoe-shaped vortex subsequently grows into a doughnut-shaped vortex ring with an intense jet-flow present in its core, forming a downwash. The doughnut-shaped vortex rings of the wing pair eventually break up into two circular vortex rings as they propagate downstream in the wake. The aerodynamic yawing and rolling torques are canceled out due to the symmetric wing kinematics even though the aerodynamic pitching torque shows significant variation with time. On the other hand, the time-varying aerodynamics pitching torque could make the body a longitudinal oscillation over one flapping cycle.

Appleman, H.

"THE FORMATION OF EXHAUST CONDENSATION TRAILS BY JET AIRCRAFT"

Bulletin American Meteorological Society, Vol. 34, No. 1, January 1953, pp. 14-20.

This paper defines the meteorological state of the atmosphere which will give rise to the formation of condensation trails (contrails) as the exhaust from an aircraft engine mixes with and saturates the environment. Three basic assumptions were made with regard to the formation of visible contrails: (1) contrails are composed of ice crystals; (2) water vapor cannot be transformed into ice without first passing through the liquid phase, thus necessitating an intermediate state of saturation with respect to water; (3) a minimum visible water content of 0.004 gm per square m is required for a faint trail and 0.01 gm per square m for a distinct trail. This last requirement proved of no importance in determining whether a trail would form, but did affect its persistence. Curves were constructed showing the critical temperature for the formation of a visible trail as a function of the pressure and relative humidity of the environment and the amount of air entrained into the exhaust. It is shown that these curves are applicable to any aircraft which has the same water to heat ratio in its exhaust as the case discussed in this report. In general, this ratio is fairly constant regardless of the type of airplane, control settings, or fuel. The major exception occurs with aircraft powered by reciprocating engines in which case a considerable portion of the heat produced may be dissipated outside of the trail. A separate, but similar, study would be necessary for each aircraft with a significantly different proportion of such heat loss.

Arasawa, T., Fujii, K. and Miyaji, K.

"HIGH-ORDER COMPACT DIFFERENCE SCHEME APPLIED TO DOUBLE-DELTA WING VORTICAL FLOWS"

Journal of Aircraft, Vol. 41, No. 4, July-August 2004, pp. 953-956

The sixth-order compact difference scheme was applied to the flow simulation over a double-delta wing and accuracy was investigated. The scheme captured two vortices without excessive dissipations, and the secondary separation vortex near the leading edge is also properly evaluated. The resulting pressure distributions on the wing showed much better agreement with the experiment than those by use of Roe's third-order scheme. The remaining problem is the accuracy of the vortex-merging location, and further investigations are necessary to improve the reliability of the simulations.

Arcas, D. R. and Redekopp, L. G.

"ASPECTS OF WAKE VORTEX CONTROL THROUGH BASE BLOWING/SUCTION"

Physics of Fluids, Vol. 16, No. 2, February 2004, pp. 452-456

Numerical simulations are used to explore the effect of blowing/suction on the characteristics of vortex shedding from a plane forebody with a rectangular base. The distribution of blowing/suction is varied to assess its role in either enhancing or suppressing the strength of shed vortices in the wake. It is shown that the amplitude of vortices in the near wake, and the required fluxes to suppress vortex shedding, scale differently depending on whether the control is exercised with blowing or with suction. These differences are rationalized in terms of local instability properties of mean velocity profiles in the near wake.

Ardonceanu, P. and Amani, G.

"REMARKS ON THE RELATION BETWEEN LIFT INDUCED DRAG AND VORTEX DRAG"

European Journal of Mechanics, B/Fluids, Vol. 11, No. 4, 1992, pp. 455-460

Among the numerous concepts which emerge from a drag analysis, some are mathematically well-defined, such as the pressure drag or the friction drag. Others of great practical interest often have a somewhat hazy definition for a real viscous fluid. The relation between the so-called 'vortex-drag' and 'lift-induced drag' is pointed out in a recent paper [Chometon and Laurent, 1990]. This short note is intended to give further clarification of the subject and some results from a relevant experimental investigation are presented. It is pointed out that the momentum balance in the wake of a lifting wing gives a correct estimate of the lift induced drag, provided that the survey area is large enough to include all the vortex energy.

Aref, H.

"VORTEX DYNAMICS OF WAKES"

Nelineinaga Dinamika, Vol. 2, No. 4, 2006, pp. 411-424.

Several problems related to the dynamics of vortex patterns as observed in wake flows are addressed. These include: The universal Strouhal-Reynolds number relation. The Hamiltonian dynamics of point vortices in a periodic strip, both the classical two-vortices-in-a-strip problem, which gives the structure and self-induced velocity of the traditional vortex street, and the three-vortices-in-a-strip problem, which is argued to be relevant to the wake behind an oscillating body. The bifurcation diagram for wake structure found experimentally by Williamson and Roshko is addressed theoretically.

Aref, H., Brens, M. and Stremler, M. A.

"BIFURCATION AND INSTABILITY PROBLEMS IN VORTEX WAKES"

Second International Symposium on Instability and Bifurcation in Fluid Dynamics, August 2006, Technical University of Denmark, Copenhagen; Journal of Physics: Conference Series, Vol. 64, 2007, 01205.

A number of instability and bifurcation problems related to the dynamics of vortex wake flows are addressed using various analytical tools and approaches. We discuss the bifurcations of the streamline pattern behind a bluff body as a vortex wake is produced, a theory of universal Strouhal-Reynolds number relation for vortex wakes, the bifurcation diagram for 'exotic' wake patterns behind an oscillating cylinder first determined experimentally by Williamson and Roshko, and the bifurcations in topology of the streamlines pattern in point vortex sheets. The Hamiltonian dynamics of point vortices in a periodic strip is considered. The classical results of von Karman concerning the structure of the vortex sheet follow from the two-vortices-in-a-strip problem, while the stability results follow largely from a four-vortices-in-a-strip analysis. The three-vortices-in-a-strip problem is argued to be relevant to the wake behind an oscillating body.

Aref, H., Stremler, M. A. and Ponta, F. L.

"EXOTIC VORTEX WAKES - POINT VORTEX SOLUTIONS"

Journal of Fluids and Structures, Vol. 22, Issues 6-7, August-October 2006, pp. 929-940.

Von Karman was the first to present a quantitative model of the 'vortex street' wake as a double row of point vortices, to determine which configurations propagate in the direction of the rows, and to consider the linear stability theory for such states. In the early literature one works with infinite rows of vortices. The vortex street is assumed to continue to infinity both upstream and downstream. Another analytical approach is to use periodic boundary conditions in the direction of the wake. This representation was used by Domm in his analysis of the instability of the Karman vortex street. Birkhoff and Fisher in 1959 were the first to treat vortices in a periodic strip as a dynamical system in its own right. We have used the periodic system to address problems of vortex wake patterns, in

particular vortex wakes that are more complicated than the traditional two-vortices-per-strip configurations. We use the term 'exotic' for such wakes. We submit that this approach can yield a number of insights, including results of direct relevance to experiments, in the same sense that von Karman's analysis has been helpful to the understanding of the regular vortex street wake, and we present the results obtained to date following this program.

Arena Jr., A. S. and Nelson, R. C.

"A DISCRETE VORTEX MODEL FOR PREDICTING WING ROCK OF SLENDER WINGS"

AIAA Paper No. 1992-4497, August 1992, Hilton Head, SC.

An unsteady, discrete vortex model has been developed in order to identify the fluid mechanisms responsible for generating wing rock of slender, sharp-edged delta wings. The solution of the unsteady flow field is coupled with the rigid body equation of motion in roll to allow for self-induced oscillations. The model has qualitatively captured all the primary flow field and motion characteristics observed in experiment. Combination of experimental and computational results indicate that wing rock is sustained by a lag in the position of the leading-edge vortices normal to the surface. Damping necessary to obtain a limit cycle is provided by rate dependent damping on the bottom surface of the wing, and damping 'lobes' generated by unsteady behavior of vortex strength.

Arend, M. F., Abdelazim, S., Santoro, D., Moshary, F., Gross, B. and Ahmed, S.

"DEVELOPMENT OF A FIBER BASED EYE SAFE COHERENT WIND LIDAR SYSTEM FOR URBAN WIND FIELD MEASUREMENTS"

Proceedings of the SPIE, Vol. 7832, October 2010, pp. 783206-1 to 783206-6.

A compact coherent wind lidar system has been developed and is being tested in an urban environment. We use polarization maintaining fiber throughout the system to improve the stability of the heterodyne detected return signal. The 1.54-micron transmitter is designed using a master oscillator and pulsed power amplifier configuration. The receiver is operated in a coaxial arrangement and balanced detection is employed to reduce the effects of relative intensity noise, allowing for operation in the shot noise limited region. Development and verification of the lidar system is enhanced by taking advantage of a set of ground based sodar, radar wind profiler and building top anemometers that are part of the New York City Meteorological Network. Operation in a coastal urban environment with a complex terrain such as New York City requires that the system be flexible enough to allow for adjustable operating conditions, tunable signal processing algorithms and user defined data products, so that the optimal performance can be chosen with a variety of practical applications in mind.

Arend, M., Campmier, M., Fernandez, A. and Moshary, F.

"APPLICATION OF LIDAR AND OTHER PROFILING TECHNIQUES TO STUDY THE IMPACT THAT SEVERE WEATHER HAZARDS HAVE ON THE NEW YORK CITY BUILT ENVIRONMENT"

28th International Laser Radar Conference, June 2017, Bucharest, Romania, published in EPJ Web of Conferences, Vol. 176, 2018, pp. 06003-1 to 06003-4.

The complexity of urban boundary layer dynamics poses challenges to those responsible for the design and regulation of buildings and structures in the urban environment. Lidar systems in the New York City Metropolitan region have been used extensively to study urban boundary layer dynamics. These systems, in conjunction with other sensing platforms can provide an observatory to perform research and analysis of turbulent and inclement weather patterns of interest to developers and agencies.

Arevalo, G., Hernandez, R. H., Nicot, C. and Plaza, F.

"PARTICLE IMAGE VELOCIMETRY MEASUREMENTS OF VORTEX RINGS HEAD-ON COLLISION WITH A HEATED VERTICAL PLATE"

Physics of Fluids, Vol. 22, 2010, pp. 053604-1 - 053604-8.

We report particle image velocimetry measurements of the collision of a vortex ring with a heated wall kept at a constant temperature. We consider the case when both the vortex ring and the thermal boundary layer generated by the vertical heated wall are stable and laminar prior to any interaction. The impingement process can be divided into two parts. (i) A ring-driven stage, where the vortex ring grows in diameter while approaching the wall and therefore it sweeps progressively an increased surface on the wall. (ii) A boundary layer-driven stage, where the vortex ring moves upward due to the thermal convective motion generated by the heated wall. In some cases, the head-on collision triggers the ring's azimuthal instability as revealed by the formation of vortical structures arranged on a wavy starlike pattern and confirmed by flow visualization. A single collision generates important velocity gradients and shear stresses along the wall accompanied with the creation of local vorticity normal to the vertical heated wall. Peak wall shear stresses occur near the point of impact of the vortex ring core.

Argentini, S., Pietroni, I., Gariazzo, C., Conidi, A., Mastrantonio, G., Pelliccioni, A., Petenko, I., Viola, A. and Amicarelli, A.

"TEMPERATURE PROFILES BY GROUND-BASED REMOTE SENSING AND IN SITU MEASUREMENTS"

14th International Symposium for the Advancement of Boundary Layer Remote Sensing, published in IOP Conf. Series: Earth and Environmental Science, Vol. 1, 2008, pp. 012025-1 - 012025-9.

This study focuses on the accuracy of the temperature profiles measured with a Doppler Radio-Acoustic Sounding System and a Microwave Temperature Profiler during a period of about 3 months in winter 2007-2008. The experiment was carried on at the experimental facility of the Institute of Atmospheric Sciences and Climate (ISAC) of the Italian National Research Council (CNR). The temperature data measured with remote sensors were verified with in situ measurements on a mast as

well as with tethered balloon data. The facimile echograms obtained with the ISAC Doppler SODAR were analyzed to understand to which extent the RASS and Radiometer temperature profiles behavior can represent the real thermal structure of the atmosphere.

Ariyur, K. B.

"PREDICTION OF DYNAMIC GROUND EFFECT THROUGH MODIFIED LIFTING LINE THEORY"

AIAA Paper 2005-4610, June 2005, Toronto, Canada.

We propose a systematic procedure for predicting ground effect forces and moments for fixed wing aircraft in subsonic flight, the first that explicitly accounts for non-zero rise/sink rates. The method extends Prandtl's lifting line theory by using an image vortex system with lifting line and trailing vortex sheet under the ground to satisfy zero normal velocity at the ground. A modified lifting line equation is obtained for the distribution on the lifting line. This is used to calculate the distribution of lift and induced drag on the wing in ground effect. Pitching moment and control surface effectiveness in ground effect are estimated using the available lift slope and pitching moment slope with the modified angles of attack in ground effect. A further extension is also made to use an image lifting surface under the ground to give more precise estimates of pitching moment and of the effects of control surface deflections in ground effect. An example calculation with an elliptical wing is used to illustrate the results and compare with available experimental results in the literature.

Arkind, K. D.

"RAYTHEON'S ADVANCED CONCEPT DEVELOPMENT ACTIVITIES IN AIR TRAFFIC MANAGEMENT"

AIAA Paper No. 2003-5771, Austin, TX, August 2003

Raytheon is participating in the NASA Virtual Airspace Modeling and Simulation program to develop new concepts in Air Traffic Management as well as building the simulation capability needed to verify these future ATM concepts. A novel approach is introduced to eliminating the constraints imposed by wake vortex avoidance, using Flight Corridors and closely spaced parallel runways to double the capacity of today's airports.

Arkind, K. D.

"REQUIREMENTS FOR A NOVEL TERMINAL AREA CAPACITY ENHANCEMENT CONCEPT IN 2022"

AIAA Paper No. 2004-5411, Providence, RI, August 2004

A primary constraint on the capacity of the National Airspace System capacity is the arrival and departure rates at our major hub airports. Raytheon has developed a novel concept for terminal area operations that significantly increases arrivals and departures. The Terminal Area Capacity Enhancing Concept (TACEC) can double the number of aircraft arriving and departing by allowing very closely spaced parallel runway usage coupled with a unique wake vortex avoidance solution. Ongoing

development efforts have included a NAS wide simulation to evaluate the potential capacity increases that TACEC can provide, as well as the feasibility of implementation at the nation's busiest airports. In addition, an analysis of the terminal airspace performance requirements for aircraft and ATM operations provides the basis for a technology roadmap exercise that delineates the necessary developments for implementation by 2022. Finally, an ongoing safety analysis provides an evaluation of the operational risks.

Arndt, R. E. A. and Keller, A. P.

"WATER QUALITY EFFECTS ON CAVITATION INCEPTION IN A TRAILING VORTEX"

Transactions of the ASME, Vol. 114, September 1992, pp. 430-438.

Tip vortex cavitation studies were made with a hydrofoil that was elliptical in planform, with an aspect ratio of 3, and having a modified NACA 662-415 profile. LDV measurements of the tangential velocity component in the vortex were used to determine that the maximum pressure in the vortex varies with lift coefficient squared, i.e., that the incipient cavitation number should follow a C_L^2 relation. This is in contradiction to previous observations that the tip vortex cavitation index varied approximately with lift coefficient to the power 1.4. By carefully monitoring the tensile strength of the water, i.e., its susceptibility to cavitation, the discrepancy was traced to the capability of the test water to sustain a tensile stress. Cavitation in 'weak' water (no tensile strength) does follow the C_L^2 relationship, whereas observations in 'strong' water (rupture considerably below vapor pressure) more closely followed the previously observed variation of C_L to the 1.4 power. Since the structure of the vortex cannot be affected by changes in the water quality, the discrepancy can be explained only by the amount of tension that can be sustained by the test water before inception occurs. Apparently a relatively larger value of tension can be sustained in the vortex as the strength of the vortex is increased. This would explain the observed deviation from the expected C_L^2 law for water with measurable tensile strength.

Arnold, R. T., Bass, H. E. and Bolen, L. N.

"ACOUSTIC SPECTRAL ANALYSIS OF THREE TORNADOES"

Journal of Acoustical Society of America, Vol. 60, No. 3, September 1976, pp. 584-593.

Three sound recordings of tornadoes have been spectrally analyzed over the frequency interval between 100 and 2000 Hz. The low-frequency analysis was limited by the response of the microphones used for the recordings; the upper frequency limit was imposed on both the microphone response and the low-signal level. One recording was made of a tornado which passed through Clay Center, Kansas on 25 September 1973. A second sound recording was made of a tornado that passed through Guin, Alabama on 3 April 1974, and a third recording was made of a tornado in Tulsa, Oklahoma on 8 June 1974. All of the recordings are of low quality and the audio information required major spectral corrections, but the data analysis does indicate that the audio emissions from the tornadoes decrease in intensity as a function of increasing frequency. An attempt has been made to correlate the data with

real (and conjectured) physical characteristics of the tornadoes and attendant atmospheric phenomena. It is clear to us from an objective analysis (and the more difficult subjective evaluation of the recordings) that identification of tornadoes based on acoustic emissions is possible.

Arntz, A. and Hue, D.

"ENERGY-BASED PERFORMANCE ASSESSMENT OF THE NASA COMMON RESEARCH MODEL"

AIAA Journal, Vol. 54, No. 1, January 2016, pp. 88-100.

Aircraft have evolved into extremely complex systems that require adapted methodologies and tools for efficient design processes. A theoretical formulation based on energy management has been recently proposed by Arntz et al. for assessing the aero-thermo-propulsive performance of future aircraft configurations. The present article focuses on the validation of its numerical implementation in a FORTRAN code for the postprocessing of Reynolds-averaged Navier-Stokes flow solutions. The flow around the wing-body NASA Common Research Model is assessed in terms of energy destruction. A 2 MW work potential associated with the lift-induced vortices is identified in the wake of the airplane. Subsequently, a six-level grid convergence study enables determining the robustness and accuracy of the energy postprocessing code. The introduction and calibration of a numerical correction allows to account for the spurious numerical vortex dissipation and to obtain an accuracy similar to the traditional near-field drag method. Finally, the postprocessing code is validated for drag prediction against computational fluid dynamics and experimental wind-tunnel data.

Arthur, W. R.

"APPLICATION OF TWO-DIMENSIONAL VORTEX THEORY TO THE PREDICTION OF FLOW FIELDS BEHIND WINGS OF WING BODY COMBINATIONS AT SUBSONIC AND SUPERSONIC SPEEDS"

NACA TN-3227, September 1954, NACA Langley Aero. Lab., Langley Field, VA

A theoretical investigation has been made of a general method for predicting the flow field behind the wings of plane and cruciform wing and body combinations at transonic or supersonic speeds and slender configurations at supersonic speeds. The wing trailing-vortex wake is represented initially by line vortices distributed to approximate the spanwise distribution of circulation along the trailing edge of the exposed wing panels.

Ash, R L., Zardadkhan, I. and Zuckerwar, A. J.

"THE INFLUENCE OF PRESSURE RELAXATION ON THE STRUCTURE OF AN AXIAL VORTEX"

Physics of Fluids, Vol. 23, 2011, pp. 073101-1 to 073101-12.

Governing equations including the effects of pressure relaxation have been utilized to study an incompressible, steady-state viscous axial vortex with specified far-field circulation. When sound generation is attributed to a velocity gradient tensor-pressure gradient product, the modified

conservation of momentum equations that result yield an exact solution for a steady, incompressible axial vortex. The vortex velocity profile has been shown to closely approximate experimental vortex measurements in air and water over a wide range of circulation-based Reynolds numbers. The influence of temperature and humidity on the pressure relaxation coefficient in air has been examined using theoretical and empirical approaches, and published axial vortex experiments have been employed to estimate the pressure relaxation coefficient in water. Non-equilibrium pressure gradient forces have been shown to balance the viscous stresses in the vortex core region, and the predicted pressure deficits that result from this non-equilibrium balance can be substantially larger than the pressure deficits predicted using a Bernoulli equation approach. Previously reported pressure deficit distributions for dust devils and tornados have been employed to validate the non-equilibrium pressure deficit predictions.

Ash, R. L.

"AXIAL VORTICES: DID RANKINE ALMOST GET IT RIGHT?"

AIAA Paper 2017-3263, June 2017, Denver, CO.

W. J. M. Rankine's 1869 axial vortex model is still in use today. By embedding a rigidly-rotating fluid cylinder within an inviscid axial vortex, the salient features of long-lived axial vortices are preserved. While that model does not predict dissipation, it also does not suffer from the non-physical core dilation behavior exhibited typically by computational fluid dynamics codes. This presentation will discuss research that has been conducted by the author, along with his colleagues and former students, focused on gaining a better understanding of the mechanisms responsible for axial vortex coherence. While we did not set out to justify Rankine's vortex model, our work on the non-equilibrium behavior of incompressible axial vortices can be employed to show how simple fluids, when subjected to potential vortex flow conditions, generate vortex cores similar to a Rankine vortex. Since the requisite non-equilibrium parameters controlling the core size and intensity are based on classical acoustic measurements for moist air, this presentation will discuss how actual weather conditions around airports can be employed to assess the potential severity of proximate vortex hazards.

Ash, R. L. and Zheng, Z. C.

"NUMERICAL SIMULATIONS OF COMMERCIAL AIRCRAFT WAKES SUBJECTED TO AIRPORT SURFACE WEATHER CONDITIONS"

Journal of Aircraft, Vol. 35, No. 1, January-February 1998, pp. 18-26

Using tower fly by data, we have developed a two-dimensional numerical simulation of wake vortex motion and decay for representative commercial aircraft. Our simulations support Squire's conjecture that the ratio of eddy viscosity to kinematic viscosity should scale linearly with circulation, which yields a nominally constant equivalent Reynolds number for all commercial aircraft sizes. We have tested the constant eddy viscosity approximation for three different aircraft configurations and six surface weather states, showing the utility of the approach in predicting wake vortex motion and decay. Subsequently,

we have shown how data from one aircraft flight test can be used to infer the decay behavior of another and we have examined the influence of the six surface weather states on the vortex decay behavior predicted for a large commercial aircraft.

Ash, R. L. and Zheng, Z. C.

"INITIALIZATION AND SIMULATION OF THREE-DIMENSIONAL AIRCRAFT WAKE VORTICES"

NASA-CR-204437, May 1997, Old Dominion Univ., Norfolk, VA

This paper studies the effects of axial velocity profiles on vortex decay, in order to properly initialize and simulate three-dimensional wake vortex flow. Analytical relationships are obtained based on a single vortex model and computational simulations are performed for a rather practical vortex wake, which show that the single vortex analytical relations can still be applicable at certain streamwise sections of three-dimensional wake vortices.

Ash, R. L., Zheng, Z. C. and Greene, G. C.

"CROSS WIND EFFECTS ON TURBULENT AIRCRAFT WAKE VORTICES NEAR THE GROUND"

AIAA Paper No. 1994-2381, Colorado Springs, CO, June 1994

A Reynolds stress transport turbulence model has been used to simulate the two-dimensional behavior of aircraft wake vortices, subjected to cross winds near the ground. The simulations have shown that turbulence effects alter vortex behavior but the direct influence of turbulence on vortex trajectories and lifetimes (near the ground) is only moderate. This study has investigated various characteristics of the atmospheric boundary layer, in order to identify the ambient variables that influence the wake vortex hazard and subsequent lifetime. Finally, an improved method for wake vortex hazard assessment has been described that can provide a more reliable estimate of the hazard.

Ashford, R.

"TERMINAL AREA PRODUCTIVITY OVERVIEW"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 1-4

Under the Terminal Area Productivity Program, NASA is developing technologies to improve airport throughput in instrument meteorological conditions (IMC). It is estimated that 60% of airborne delays are due to conducting approaches to airports under IMC. In visual terminal operations, responsibility for maintaining safe separation during takeoff, initial climb-out, approach, landing and roll out rests with the flight crew of each airplane. Conversely, in non-visual terminal operations, responsibility for maintaining safe separation rests with Air Traffic Control. The result is a set of separation standards that varies significantly between visual and non-visual conditions. A major part of the program is devoted to safely optimizing longitudinal and lateral spacing between aircraft to approach that

attainable in visual conditions. This work includes both flight deck and ground-based advanced automation to improve pilot and controller situational awareness and decision making capabilities. Technologies to expedite surface operations in low visibility conditions are also being developed.

Ashkenas, I. L. and Johnson, W. A.

"WAKE VORTEX HAZARD DEFINITION PROGRAM"

TR-1025-3, July 1974, Systems Tech. Inc., Hawthorne, CA

This report documents the development of a vortex hazard definition program. Implementation of this program will provide an important step toward the realization of an ultimate system that will safely provide reduced traffic separations at congested airports. The problem is conceptually a simple one: with reduced separations there is a greater potential hazard from vortex encounters. The main point is that we need to assure safe operations with minimum separations that are tailored to the actual hazard. In order to do this we must consider the possibility of a worst case encounter; and if such encounters are potentially catastrophic, we must assure that the probability of such an event is acceptably small. To do this requires a more precise definition of hazard than simple rules of thumb. The central role of appropriate computer simulation and analysis is emphasized. All program elements feed into a progressively improved simulation, where critical interactions are assessed in the presence of all other inputs. We must depend on computer modeling because of the many possible critical situations; we must consider the pilot's probable (recovery) control behavior; and we must predict vortex location and strength with minimum uncertainty. Then we must establish realistic, tailored hazard volumes.

Ashley, S.

"QUIETING KILLER WAKES"

Scientific American, Vol. 286, No. 2, February 2002, pp. 24-25

Engineers are working on ways to detect hazardous wake vortices so pilots can avoid them or to design aircraft that leave safer skies behind them. If implemented, these new technologies could boost the number of planes that airports could handle, thus cutting delays and enabling increased commercial air traffic in coming years.

Ashmore, B. R., Kimura, A. and Skeith, R. W.

"DATA PROCESSING AND DISPLAY OF LASER DOPPLER EXPERIMENTAL RESULTS, VOLUME 1"

NASA-CR-150441, September 1976, Arkansas Univ., Fayetteville, A.

Contract activities performed in developing a laser Doppler system for detecting, tracking, and measuring aircraft wake vortices are summarized. The computer program for processing and displaying the Dust Devil experimental data is presented. Program listings are included in the appendix.

Ashok, A. and Smits, A. J.

"THE TURBULENT WAKE OF A SUBMARINE MODEL IN PITCH AND YAW"

AIAA Paper 2013-1121, January 2013, Grapevine, TX.

The objective of the present study is to understand how the pitch and yaw angle affect the mean flow and turbulence in the wake of the DARPA SUBOFF, an idealized submarine model. Measurements in the wake were performed at $Re = 2,400,000$. Mean velocity and one-component turbulence measurements were performed using Pitot probes and single normal hot wires in the span-wise plane, 10 diameters downstream of the trailing edge. The range of measured angles of attack and yaw angles were limited to between 0 and 12 degrees in part to avoid wind tunnel interference effects. Flow visualization in water at $Re = 4,000$ was also performed to inform the wake patterns observed at higher Reynolds number.

Asselin, D. J. and Williamson, C. H. K.

"VORTEX PAIR IMPINGING ON A HORIZONTAL GROUND PLANE"

Physics of Fluids, Vol. 25, No. 9, 2013, pp. 091104-1 to 091104-2.

In this work, we employ a water tank equipped with a long set of computer-controlled flaps. These flaps are lowered into the tank and closed, much as one would close a book, to generate a counter-rotating vortex pair. This primary vortex pair then descends under its own induced velocity toward a transparent acrylic ground plane. Upon interaction with the boundary, the vortices drive fluid in a boundary layer against an adverse pressure gradient. This ultimately causes flow separation and the rollup of a secondary vortex pair of opposite sign vorticity. Two principal phenomena are observed. The first is significant axial flow in each vortex tube. Because the Crow instability causes displacements in a plane oriented at approximately 45 degrees to the horizontal, the 'troughs' of the sinusoidal vortex tube, at which the vortices are closest together, interact with the ground before the 'peaks.' The result is a strong motion of the fluid away from the region of closest approach, producing bulbous regions of vorticity at the peaks of the vortex. The second phenomenon occurs in the secondary vorticity. Here, structures that appear to be rebounding vortex rings, located between the deformed primary vortices, are clearly observed. It is particularly important to note that the precise structures produced are highly dependent on the extent to which the Crow instability has developed prior to contact with the boundary.

Asselin, D. J. and Williamson, C. H. K.

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Asselin, D. J. and Williamson, C. H. K.

"FORMATION OF SMALL-SCALE VORTEX RINGS FROM VORTEX PAIRS CLOSE TO THE GROUND"

66th Annual Meeting of the APS Division of Fluid Dynamics, Vol. 58, No. 18, November 2013, Pittsburgh, PA.

In this research, we examine the effect of a solid boundary on the dynamics and instabilities of a pair of counter-rotating vortices. An isolated vortex pair is subject to a short-wave elliptic instability and a long-wave Crow instability. Near a wall, the boundary layer between the primary vortices and the wall can separate, leading to the generation of secondary vorticity. These secondary vortices can be subject to small-scale instabilities as they come under the influence of the primary vortices. In contrast, in the present study we are interested in the long-wave Crow instability interrupted by interaction with a wall. This can cause significant axial flow, resulting in a periodic concentration of fluid containing vorticity at the peaks of each wavy vortex tube and a corresponding evacuation of fluid containing vorticity from the troughs. It appears that this axial flow is driven at least in part by the formation of vortex ring-like structures in the secondary vortex as it is deformed by the primary vortex. Furthermore, additional small scale-vortex rings evolve from the secondary vorticity and from the concentrated vortical regions in the primary vorticity. In both cases, these rings cause vorticity to rebound away from the ground.

Astegiani, G., Casanova, D., Isambert, E., Van Engelen, J. and Treve, V.

"FINAL REPORT WP1000 SYSTEMS REQUIREMENTS"

IST-2001-34729, May 2003, National Aerospace Laboratory, Amsterdam, The Netherlands

This document constitutes the final report from ATC-WAKE WP 1000 dedicated to the specification of Operational Requirements, Operational Concept and Procedures, User Requirements and System Requirements for an ATC system integrating wake vortex prediction and detection capabilities.

Atashbaz, G. and Ommian, M.

"EXPERIMENTAL INVESTIGATION OF VORTEX FLOW OVER AN 80 DEGREE/60 DEGREE DOUBLE DELTA WING AT SIDESLIP"

Journal of Aircraft, Vol. 43, No. 3, May-June 2006, pp. 840-842.

A series of qualitative and quantitative experimental investigations into the effect of angle of attack and sideslip on the aerodynamic behavior of a sharp leading-edge 80 deg/60 deg double delta wing were conducted. Surface oil-flow and laser light sheet visualizations, as well as surface pressure measurements, were performed on the strake and wing upper surface. The following observations are made. (1) Suction peak increases with increasing angle of attack symmetrically on both sides of the double delta wing before vortex breakdown occurs. (2) Increasing sideslip will cause strong asymmetric vortices over starboard and port sides of the wing, which causes different lift characteristics and as a result causes rolling moment. This may produce difficulties in stability and control of the wing.

Atassi, O. V., Bernoff, A. J. and Lichter, S.

"INTERACTING VORTEX AND VORTEX LAYER: HOW LENGTH SCALE AFFECTS ENTRAINMENT AND EJECTION"

AIAA Journal, Vol. 36, No. 6, June 1998, pp. 924-928

A contour dynamics model of the interaction between a point vortex and a layer of constant vorticity, bounded below by a slip wall and above by irrotational flow, is studied. The height of the vortex above the layer establishes a length scale that is found to have a strong influence on both the evolution of the layer and the vertical displacement of the vortex. A vortex far above the boundary layer generates long-wavelength disturbances. These exhibit early-time growth, which saturates, taking on the shape of a vortex-like structure, suggesting that a vortex far above a boundary layer can create another one within the layer. Concurrently, entrainment of irrotational flow deep into the layer occurs within a narrow crevice. Alternatively, for a vortex initially placed close to the layer, a short-scale disturbance occurs that exhibits rapid, continuous growth that eventually rolls up around the vortex. Here, accounting for the vertical displacement of the vortex is necessary to accurately determine the interface evolution. The results support the contention that a vortex can induce ejection and roll up of the boundary layer and entrainment of irrotational flow into the layer.

Atassi, O. V., Lichter, S. and Bernoff, A J.

"THE INTERACTION OF A POINT VORTEX WITH A BOUNDARY LAYER LEADING TO ERUPTION"

AIAA Paper No. 1996-2140, New Orleans, LA, June 1996

A model for entrainment of irrotational flow into a boundary layer, and the eruption and rollup of vorticity away from the wall, is studied. The model consists of a point vortex and a layer of constant vorticity, bounded below by a wall and above by an irrotational flow. Contour dynamics is used to compute the pathline of the vortex and the evolution of the interface which delineates vortical flow from irrotational flow. Four cases are studied for which the ratio of vortex strength to initial distance of

the vortex above the interface is kept fixed. With this constraint, the initial vortex-induced velocity evaluated at a scaled distance along the interface is equal in all cases. Consequently, a vortex far above the boundary layer generates long-wavelength disturbances on the interface. These exhibit early-time growth which saturate as their amplitude becomes large. The interface takes the shape of a vortex-like structure as it overturns, suggesting that a vortex far above a boundary layer can create another one within the layer. Concurrently, entrainment of irrotational flow deep into the layer occurs within a narrow crevice. Though the vortex moves towards the layer during the course of its interaction, the change in its induced velocity on the interface is not dynamically significant. Alternatively, for a vortex initially placed close to the layer, a short-scale disturbance occurs for which the change in induced velocity due to the vertical displacement of the vortex is significant. The disturbance exhibits rapid, continuous growth that eventually rolls up around the vortex.

Atias, M. and Weihs, D.

"MOTION OF AIRCRAFT TRAILING VORTICES NEAR THE GROUND"

Journal of Aircraft, Vol. 21, No. 10, October 1984, pp. 783-786

A theoretical study of the motion of a two-dimensional vortex pair, such as obtained in a subsonic aircraft wake moving near the ground, is described. The wake motion, analyzed by a discrete vortex method, is shown to be characterized by a repeating rebounding phenomenon, resulting in a spiral path, with a general upward and outward motion, after the initial approach to the ground. It is shown that the cause of the rebounding and the oscillations observed in the trajectories of such vortex pairs is the boundary layer generated near the ground. This vorticity separates and gyrates around the vortices of the pair.

Atkin, J. A. D., Burke, E. K., Greenwood, J. S. and Reeson, D.

"A META-HEURISTIC APPROACH TO AIRCRAFT DEPARTURE SCHEDULING AT LONDON HEATHROW AIRPORT"

9th International Conference on Computer-Aided Scheduling of Public Transportation, San Diego, CA, August 2004

London Heathrow airport is one of the busiest airports in the world. Moreover, it is unusual among the world's leading airports in that it only has two runways. At many airports the runway throughput is the bottleneck to the departure process and as such it is vital to schedule departures effectively and efficiently. For reasons of safety, separations need to be enforced between departing aircraft. The minimum separation between any pair of departing aircraft is determined not only by those aircraft but also by the flight paths and speeds of aircraft that have previously departed. Departures from London Heathrow are subject to physical constraints that are not usually modelled in departure runway scheduling models. There are many constraints which impact upon the orders of aircraft that are possible and we will show how these constraints either have already been included in the model we present or can be included in future. The runway controllers are responsible for the sequencing of the

aircraft for the departure runway. This is currently carried out manually. In this paper we propose a metaheuristic-based solution for determining good sequences of aircraft in order to aid the runway controller in this difficult and demanding task. Finally, some results are given to show the effectiveness of this system and we evaluate those results against manually produced real world schedules.

Attwooll, V. W.

"SEPARATION CRITERIA FOR SUPERSONIC TRANSPORTS AND OTHER ASPECTS OF TRAFFIC CONTROL"

Journal of the Institute of Navigation, Vol. 15, No. 2, Summer 1968, pp. 199-204.

This paper discusses the studies made of the traffic system for the supersonic transport at the RAE. We first discuss the design for the oceanic traffic system having regard to the performance characteristics of the aircraft, to the characteristics of the atmosphere at the heights to be flown and to possible restriction of supersonic flight overland. Cost effectiveness studies give desirable values for oceanic separation minima. We then consider the desirable navigation specification to achieve these minima. Finally, we discuss the control of the aircraft during the domestic oceanic transition and in the terminal area.

Attwooll, V. W.

"THE EFFECTS OF TRAILING VORTICES ON THE SAFE CAPACITY OF AIR ROUTES AND AIRPORTS"

Tech. Memo. Math 6702/2, July 1967, Royal Aircraft Establishment, Farnborough, England

Although the danger to aircraft of flying into the trailing vortex shed by another aircraft has been stressed many times, there is still too little known about the characteristics of vortices to enable the relation between the vortex hazard and the separation minima used by Air Traffic Control to be expressed in quantitative terms. The memorandum shows that present knowledge is insufficient to eliminate the possibility that the vortex hazard could have a marked effect both on the capacity of airports and on the lethal risk attendant on a close approach following inadvertent loss of separation between two aircraft en route.

Aubrun, S., Loyer, S., Espana, G., Hayden, P. and Hancock, P.

"EXPERIMENTAL STUDY ON THE WIND TURBINE WAKE MEANDERING WITH THE HELP OF A NON-ROTATING SIMPLIFIED MODEL AND OF A ROTATING MODEL"

AIAA Paper 2011-0460, January 2011, Orlando, FL.

The present work completes a previous study of the present authors that compared, through wind tunnel experiments, the wake properties of a model of a 3-blade rotating wind turbine and of a porous disc made of metallic mesh. The main goal is to determine, in the context of numerical or experimental approaches, the acceptable degree of modelling of the wind turbine to study in the far-wake. The previous study showed that the wake expansion was similar for both models and the specific signatures

induced by a rotating wind turbine (tip vortices and add of rotational momentum) were indiscernible from $x = 3D$ downstream of the rotating model. The present results show that the wake meandering due to the large turbulence length scales of the freestream ABL-like flow is detected and its amplitude is similar for both models. Furthermore, the meandering process detected in the present study is proven to be horizontal and not vertical. To conclude, one can notice that no discrepancy is detected in the meandering process of the wake downstream of a porous disc or of a rotating wind turbine in the present experimental conditions. It tends to prove that modelling a turbine through the actuator disc concept is adequate to study the turbine far-wake in many situations (on condition that the freestream turbulence intensity is relatively high).

Audenaerd, L.

"CHARACTERIZATION OF SURFACE AND ALOFT WINDS FOR ADVANCED PARALLEL RUNWAY OPERATIONS"

Journal of the Transportation Research Board, Vol. 2300, Issue 1, December 2012, pp. 49-58.

The increase in demand for air travel throughput has resulted in an effort to identify novel techniques for improving efficiency. One such effort targets the barrier imposed by wake turbulence separation standards -- reducing inter-aircraft spacing during radar operations. Recently, concepts have focused on exploiting the effects of wake transport under wind fields by developing wind-dependent procedures that mitigate wake hazards during favorable wind conditions. However, the challenge regarding computing benefits during conditional time epochs requires methodology designed for a niche modeling area that even sophisticated airport capacity simulation models lack. This work attempts to augment the capacity computation by presenting a characterization of the favorable crosswind availability across a range of thresholds and aloft monitoring heights based on Rapid Update Cycle and aviation system performance measure weather data. The focus is on presenting a generalization of wind behavior and on providing insight into the effects of the wind on the applicability of wind-dependent wake-based procedures. Data for nine major U.S. airports currently operating closely spaced parallel runways are analyzed.

Audenaerd, L.

"ESTIMATING APPROACH PATH COVERAGE OF AIRCRAFT-DERIVED METEOROLOGICAL DATA IN ADVANCED AIR TRAFFIC MANAGEMENT APPLICATIONS"

Journal of the Transportation Research Board, No. 2449, 2014, pp. 53-63.

If appropriately equipped, aircraft traveling throughout the global air space have the unique capability to measure and report high-resolution meteorological data, under all weather conditions. These data can have high economic value for both aviation and nonaviation uses by communicating a dense picture of weather conditions from thousands of ad hoc sensors operating daily in the global air space over areas of an aviation operational interest. However, ensuring that the technology provides adequate levels of service and safety requires a clear understanding of system performance

characteristics in conjunction with sensor and data link capabilities, broadcast frequencies, equipage rates, and operational service environmental requirements. This paper explores the density of coverage as a measure of performance by presenting the problem as a stochastic area coverage model of a homogeneous dynamic wireless ad hoc sensor network. A model was developed to relate the density needs of various advanced air traffic management applications to the spatial and temporal coverage of aircraft-sensed meteorological data in the airport terminal area. A comprehensive experimental design is presented with varying aircraft equipage rates, message broadcast frequencies, coverage granularities, and traffic demand levels. Infrastructure and sensor limitations are included to capture some realism within the model. Results are determined by solving this variation on a traditional set covering model using Monte Carlo simulation techniques.

Audenaerd, L. and Lunsford, C.

"APPLYING IMPROVED WIND AND AIRCRAFT PERFORMANCE DATA IN WAKE PROCEDURE CONCEPTS"

2014 Integrated Communications Navigation and Surveillance (ICNS) Conference, April 2014, Herndon, VA.

As NextGen concepts seek increasing airport throughput, separation from naturally occurring wake turbulence becomes a limiting factor in the pursuit of capacity improvements in many cases. In recent years, the implementation of fixed procedural changes that reduce wake separations while maintaining safety have been very successful. Further opportunities for reducing wake constraints have led to exploiting specific meteorological conditions to mitigate wake hazards. As an example, one such program, entitled Wake Turbulence Mitigation for Departures, ensures safe reduction of successive departure separations based on dynamic crosswind conditions. Availability of these conditions, however, is limited by the abilities of the wind detection system -- its sensing ability, data reliability and forecasting accuracy. Recent efforts are addressing these limitations by exploring how the use of better knowledge of wind and aircraft performance can increase availability or enable the design of further wake turbulence mitigation arrival and departure procedures. Additionally, recent advancements in aircraft flight track data assimilation have led to a deeper understanding of aircraft operational behavior during landing and take-off cycles. The confluence of these efforts is currently being leveraged to develop more sophisticated wake mitigation applications. This paper provides an overview of recent progress in developing broad data access and collection of weather and aircraft positional data; prospective applications that would leverage these data; and the relationship between the data density, or supply-side, requirements and the associated application demand needs.

Audenaerd, L., Domino, D., Lang, S., Lunsford, C., Smith, A. P. and Tittsworth, J.

"INCREASING AIRPORT ARRIVAL CAPACITY IN NEXTGEN WITH WAKE TURBULENCE AVOIDANCE"

Integrated Communications, Navigation and Surveillance Conference, May 2009, Arlington, VA.

Arrival capacity at major airports is a primary constraint that must be overcome to reach the Next Generation Air Transportation System (NextGen) capacity goals. At the nation's busiest airports with

closely spaced parallel runways for arrivals, capacity can be reduced significantly when weather at these airports falls below visual approach minima. When visual approaches can be used for arriving aircraft, pilots can apply their experience and judgment to position their aircraft to avoid wake turbulence generated by other aircraft they are following to the airport. This practice allows for the best arrival capacity to be achieved in good weather. When ceiling and visibility fall below that required for visual approaches, airports that would normally arrive on two parallel runways spaced less than 2500 feet apart, must discontinue parallel approaches, thus reducing the arrival rate to what can be achieved with a single runway. This reduction in capacity is due to the air traffic control requirement that parallel runways spaced this closely must be treated as one runway for application of wake turbulence separation. A new wake turbulence procedure has recently been approved for use at several airports that allows arrivals at these airports to reduce separation between aircraft on parallel approaches in weather below visual approach minima using a parallel dependent stagger arrival operation. This procedure, documented in JO 7110.308, allows aircraft to arrive in staggered pairs, with Large and Small wake category aircraft in the lead. With this procedure, approximately half of the capacity normally lost due to deteriorating weather can be regained. Additional procedures are being explored, such as Wake Turbulence Mitigation for Arrivals (WTMA) that will allow additional gains in capacity by including additional airports with more closely spaced runways, and additional wake category aircraft participating as leaders in this parallel dependent stagger approach procedure. This paper provides an overview of the WTMA concept and describes analysis techniques used to develop initial estimates of the capacity improvement that various phases of WTMA will provide.

Augenstein, E., Leopold, F., Richard, H. and Raffel, M.

"SCHLIEREN TECHNIQUES IN COMPARISON: THE BACKGROUND ORIENTED METHOD VERSUS VISUALIZATION WITH HOLOGRAPHIC FILTERS"

4th International Symposium on Particle Image Velocimetry, Paper 1191, September 2001, Gottingen, Germany.

Within this paper two recently developed visualization techniques are presented. The results of the Background Oriented Method, are compared to the flow-field visualizations, obtained by using the holographic filters from ISL. Both, the background oriented schlieren technique as well as the visualization with holographic filters were used to represent the index gradients of aerodynamic flows. The investigations have been carried out in the ISL blow-down wind tunnel at a Mach number of 3. A canard-wing combination was used in order to study the shock-vortex interaction phenomenon.

Augere, B., Besson, C., Dolfi, A., Fleury, D., Goular, D. and Valla, M.

"1.5 MICRON LIDAR FOR HELICOPTER BLADE TIP VORTEX DETECTION"

Advanced In-Flight Measurement Techniques, Research Topics in Aerospace, edited by F. Boden et al, 2013, Springer-Verlag Berlin Heidelberg, pp. 187-194.

The objective in the ONERA study in the project 'Advanced In-flight Measurement Techniques' is to assess the capability of an on-board LIDAR technique to investigate in-flight tip vortices behavior. This paper presents the design of a 1.5 micron LIDAR sensor dedicated to tip vortex characterization and tests on ground during trials on a DLR helicopter in hover flight. The relevant information resulting from these trials is the tip vortex velocity field as well as the time evolution of the vortex. The technical challenge here is to characterize a very small phenomenon at short range: the core radius varies from typically 10 to 30 mm as the vortex ages. The study results show that LIDAR technique is promising for onboard measurement during flight. The velocity measurement is direct and absolute (no calibration needed) and its accuracy can be up to 0.25 m/s and commonly 1 m/s. However, seeding is necessary to realize a compact and reliable LIDAR system with components 'off the shelf': in the framework of flight trials, clouds could provide efficient seeding enabling the use of LIDAR as a powerful technique for tip vortex characterization.

Augere, B., Valla, M., Durecu, A., Dolfi-Bouteyre, A., Goular, D., Gustave, F., Planchat, C., Fleury, D., Huet, T. and Besson, C.

"THREE-DIMENSIONAL WIND MEASUREMENTS WITH THE FIBERED AIRBORNE COHERENT DOPPLER WIND LIDAR LIVE"

Atmosphere, Vol. 10, No. 549, September 2019.

A three-dimensional (3D) wind profiling Lidar, based on the latest high power 1.5 μ m fiber laser development at Onera, has been successfully flown on-board a SAFIRE (Service des Avions Français Instrumentés pour la Recherche en Environnement) ATR42 aircraft. The Lidar called LIVE (Lidar VEnt) is designed to measure wind profiles from the aircraft down to ground level, with a horizontal resolution of 3 km, a vertical resolution of 100 m and a designed accuracy on each three wind vector components better than 0.5 m.s⁻¹. To achieve the required performance, LIVE Lidar emits 410 J laser pulses repeating at 14 KHz with a duration of 700 ns and uses a conical scanner of 30° total opening angle and a full scan time of 17 s.

Azlin, M. A., Taib, C. F., Kasolang, S. and Muhammad, F. H.

"CFD ANALYSIS OF WINGLETS AT LOW SUBSONIC FLOW"

Proceedings of the World Congress on Engineering 2011, Vol. 1, July 2011, London, U.K.

A winglet is a device attached at the wingtip, used to improve aircraft efficiency by lowering the induced drag caused by wingtip vortices. It is a vertical or angled extension at the tips of each wing. Winglets work by increasing the effective aspect ratio of a wing without adding greatly to the structural stress and hence necessary weight of the wing structure. This paper describes a CFD 3-dimensional winglets analysis that was performed on a rectangular wing of NACA65,218 cross sectional airfoil. The wing is of 660 mm span and 121 mm chord and was analyzed for two shape configurations, semicircle and elliptical. The objectives of the analysis were to compare aerodynamic characteristics of the two winglet configurations and to investigate the performance of the two winglets shape simulated at

selected cant angle of 0, 45 and 60 degrees. The computational simulation was carried out by FLUENT 6.2 solver using Finite Volume Approach. The simulation was done at low subsonic flow and at various angles of attack using Spalart-Allmaras couple implicit solver. A comparison of aerodynamics characteristics of lift coefficient, drag coefficient and lift to drag ratio, L/D was made and it was found that the addition of the elliptical and semi-circular winglet gave a larger lift curve slope and higher Lift-to-Drag Ratio in comparison to the baseline wing alone. Elliptical winglet with 45-degree cant angle was the best overall design giving about 8 percent increase in lift curve and the best Lift-to-Drag Ratio.

Azuma, A., Saito, S. and Kawachi, K.

"RESPONSE OF A HELICOPTER PENETRATING THE TIP VORTICES OF A LARGE AIRPLANE"

Vertica, Vol. 11, No. 1/2, 1987, pp. 65-76.

The dynamic response of helicopters penetrating a pair of trailing vortices of a jumbo jet is analyzed. The rotor aerodynamic forces which are fully coupled with the body motion with six degrees of freedom are calculated by using the local momentum theory (LMT). The wake vortices of the jumbo jet are assumed to be a frozen gust and are disturbed by the blade motion. The time histories of the dynamic behaviors of the helicopter as well as the blade motion are presented for the various parameters such as the distance between the helicopter and the jumbo jet, the type of helicopter rotor, and the flight path angle with respect to the trailing vortex of the jumbo jet.

Azuma, R., Fox, J. and Furmanski, C.

"EVALUATING VISUALIZATION MODES FOR CLOSELY-SPACED PARALLEL APPROACHES"

Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting, 2005, pp. 35-39

Raytheon's TACEC (Terminal Area Capacity Enhancement Concept) proposes to increase airspace capacity by using closely-spaced formations of arriving and departing aircraft to greatly increase airport capacities. However, a blunder in a tightly-spaced formation could cause a collision with another aircraft or its wake vortices. Therefore, humans need tools and visualization aids to detect and respond to blunders. This paper is the first in a series of experiments to evaluate the ability of different visualization modes to enable detection of lateral blunders. We tested four viewpoints, one warning aid, and three blunder speeds in a within-subjects design. This study had twelve participants. The main result was that changing the viewpoint made a large difference; the cockpit view was by far the worst. Blunder detection varied by speed and was difficult in the presence of noise. Future experiments should use more realistic simulators and pilots as participants.

Baals, D. B. and Mourhess, M. J.

"NUMERICAL EVALUATION OF THE WAKE-SURVEY EQUATIONS FOR SUBSONIC FLOW INCLUDING THE EFFECT OF ENERGY ADDITION"

NACA ARR-L5H27, October 1948, Langley Aeronautical Lab., Langley Field, VA

Direct-reading tables and charts are presented for determining the drag or thrust coefficients from wake-survey measurements in the subsonic speed range. For flows wherein no energy is added, the point drag coefficient is shown to be an explicit function of the stream Mach number, the static-pressure coefficient at the wake station, and the total-pressure-loss coefficient. Values of the point drag coefficient are tabulated for a wide range of values of these parameters. Inasmuch as the tabulated coefficients (either drag or thrust) represent the point values, which are independent of the integration of the wake, the charts or tables in the form presented are general in application. For flows wherein energy is added, such as flows behind propellers or heated radiators, an additional parameter, which is a function of the stagnation-temperature rise, must be considered. Values of the point drag coefficient that include the effects of the addition of energy are tabulated.

Baart, D., Monk, H. and Schweiker, M. L.

"AIRPORT CAPACITY AND DELAY ANALYSES"

DOT-FAA-CT-TN91/18, April 1991, FAA Technical Center, Atlantic City, NJ

The benefits achievable in terms of reduced delay and capacity gained at several major airports if products of the Wake Vortex Program were implemented resulting in reduced intrail separation standards is addressed. These theoretical separation standards were developed from products of the Wake Vortex Program and were used in a simulation of runway operations at John F. Kennedy (JFK), Boston (BOS), and St. Louis (STL) airports. These products include Vortex Advisory System (VAS), Wake Vortex Avoidance System (WVAS), Wake Vortex Detection/Monitoring System. In addition to site specific airports, generic runway configurations were explored as a means of grouping many airports with similar configurations. The estimates derived include delay time saved in dollars per day and capacity gained in operations per hour for each airport evaluated. Considerable benefits to the airlines and the economy could be achieved if these wake vortex products were implemented resulting in reduced separation standards.

Baart, D., Rovinsky, R. B., Monk, H. and Schweiker, M.

"EFFECT OF REDUCED INTRAIL SEPARATIONS ON CAPACITY"

Proceedings of the Aircraft Wake Vortices, Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 27-1 - 27-22

Alleviating the congestion of our airports has been a major concern of the FAA and the airlines. Conservative separation standards, now in effect, increase arrival and departure delay and reduce airport capacity. Several products of the FAA's Wake Vortex Program, if implemented, will permit reduced separation standards in terminal areas, in addition to improving safety. Using the Runway Delay Simulation (RDSIM) Model, which emulates runway operations based on historical data, we examined these theoretical separation standards on capacity and delay at John F. Kennedy (JFK), Boston (BOS), and St. Louis (STL) airports. Generic runway configurations were also explored as a means of

grouping many airports with similar runway configurations. We also used SIMMOD, which provides considerable detail on the airfield and airspace of an airport, to analyze the benefits possible at Dallas Fort Worth (DFW) and Chicago O'Hare (ORD) from developing and installing future wake vortex detection/monitoring systems as well as changing future separations standards. This paper presents the results of the above analyses, which indicate that the reduced separation standards can produce significant benefits to the aviation industry and economy. However, these benefits can only be realized by safely coordinating operational changes with air traffic procedures.

Babie, B. M.

"AN EXPERIMENTAL AND ANALYTICAL STUDY OF THE STABILITY OF COUNTER-ROTATING VORTEX PAIRS WITH APPLICATIONS FOR AIRCRAFT WAKE TURBULENCE CONTROL"

Ph.D. Thesis, April 2008, Notre Dame, Indiana.

Three principal objectives served to focus the research project that is presented in this dissertation. The first two objectives were to develop an improved understanding of the wake configurations that were conducive to large instability growth rates and to subsequently use quantitative methods to identify the instability modes that dominate the far-field wake dynamic. With a clear understanding of the physics of an unstable aircraft wake, the third objective was to use this newly attained information to recommend methods for a reliable wake control strategy. A compilation of flow visualization results shows a design space of counter-rotating wake configurations, defined by the circulation and span ratios, where rapidly amplifying instabilities are consistently seen to exist. This design space is also seen to encompass rigidly-translating wake systems. A combination of quantitative flow visualization estimates, hot-wire anemometry and an analytical stability analysis was successful in identifying two forms of bending wave instability, namely the long and short-wave modes. Having identified two bending instability modes in the experimental wake, it was possible to suggest a strategy by which these modes could be exploited for the control of aircraft wakes.

Babie, B. M. and Nelson, R. C.

"FLOW VISUALIZATION STUDY OF FAR FIELD WAKE VORTEX INTERACTIONS"

11th International Symposium on Flow Visualization, Notre Dame University, Notre Dame, IN, August 9-12, 2004

An experiment to study the interaction of a wake consisting of four vortices is currently under development in the Hessert Laboratory at the University of Notre Dame. The four vortices are created by an apparatus consisting of four half span high aspect ratio wings. Each wing is mounted to a stepper motor that permits accurate control of the wing angle of attack. Furthermore, the lateral spacing between the wings can be manually adjusted. Thus, the spacing, circulation and sense of rotation of each vortex in the wake can be controlled. The goal of this study is to investigate how a wake consisting of four vortices can be made unstable so that it decays rapidly in the downstream direction. The vortex instability modes under investigation generally occur at large distances downstream from

the origin of their generation. The primary method of validating the new multiple vortex interaction facility is through visualization of the vortices. A major challenge in observing the extent of attenuation in the far field of the wake is in maintaining seeding of the vortex structures at large distances downstream. Methods for achieving such a flow seeding will be discussed in detail. The visualization method that has shown the most promise for tracking multiple vortices many span lengths downstream of the wake generating device is through helium bubble visualization. This paper discusses the use of helium bubbles to mark the vortices, lighting and other issues that needed to be resolved to be able to track the vortex wake evolution.

Babie, B. M. and Nelson, R. C.

"AN EXPERIMENTAL INVESTIGATION OF BENDING WAVE INSTABILITY MODES IN A GENERIC FOUR-VORTEX WAKE"

Physics of Fluids, Vol. 22, 2010, pp. 077101-1 - 077101-15.

An experimental study of a planar wake consisting of four vortices that simulate the trailing vortex wakes generated by transport airplanes in either takeoff or landing configurations is presented. The objective of this study was to examine naturally occurring wake instabilities. Specifically, the focus of the study was centered on bending wave instabilities of which the Crow instability represents a particular case. A unique method of generating a four-vortex wake was developed for this study. The four-vortex wake generating device permitted direct variation of the spacing between vortices as well as control over the vortex circulation strength. Two quantitative flow visualization experiments were instrumental in identifying wake configurations that were conducive to the rapid growth of bending wave modes and in the identification of the long-wavelength mode. Detailed experiments were also conducted to examine the flow structure in the near-field or roll-up region using a four sensor, hot-wire probe that could measure all three velocity components in the wake simultaneously. The results of both the flow visualization and hot-wire experiments indicate that the long-wavelength mode and the first short-wavelength mode likely dominate the far-field wake physics and may potentially be utilized in a wake control strategy.

Babie, B. M. and Nelson, R. C.

"WAVELENGTH AND AMPLITUDE MEASUREMENT OF AN UNSTABLE WAKE VORTEX BENDING MODE VIA HELIUM-BUBBLE VISUALIZATION"

13th International Symposium on Flow Visualization, Nice, France, July 2008

This paper describes a research study that examines the potential of exciting instability modes in a trailing vortex wake to cause breakup and decay of these hazardous wake structures. A four-vortex model has been selected for this study as it is representative of a landing aircraft wake; a flight stage that is most prone to wake encounters. Previous work done by the authors has resulted in the identification of a region of counter-rotating wake configurations that are conducive to large temporal instability growth rates. This region is also observed to include those configurations which are known

to translate rigidly. The driving hypothesis of the current work is that the observed unstable motion is a long-wavelength instability that is driven by the mutual interaction of the tip/flap vortex pair on each side of the wake centerline. The helium-bubble visualization technique has been used as an effective tool for the identification of the long-wavelength instability. The data attained from visual images of the wake have been used to obtain quantitative estimates of the bending mode wavelength and amplitude for comparison with linear stability theory.

Babie, B. M. and Nelson, R. C.

"AN EXPERIMENTAL STUDY OF WAKE VORTEX INSTABILITIES"

AIAA Paper 2008-363, Reno, NV, Jan. 2008

An investigation of the stability of a four-vortex wake has been conducted in the atmospheric boundary layer wind tunnel at the University of Notre Dame. Four independent wing models were used to create a generic four-vortex wake, such that the effects of circulation strength and vortex span could easily be studied. Helium bubble flow visualizations provide sufficient evidence of the persistence of a long-wavelength instability driven primarily by the strain field between the inboard-outboard vortex pair for a specific set of wake configurations. A quantitative investigation into the near-field development of these wakes via hot-wire anemometry further indicates the development of the elliptical form of short-wavelength instability. The experimental measurements of a short-wavelength perturbation frequency was found to compare favorably to that predicted by theory.

Babigian, R. and Hayashibara, S.

"COMPUTATIONAL STUDY OF THE VORTEX WAKE GENERATED BY A THREE-DIMENSIONAL WING WITH DIHEDRAL, TAPER, AND SWEEP"

AIAA Paper 2009-4107, June 2009, San Antonio, Texas.

A preliminary CFD study was conducted to compare the wingtip vortices and induced drag generated by three wing-configurations at cruise conditions. The geometry for a clean wing, a wing with winglets, and a wing with raked wingtips were modeled in CATIA and numerically analyzed using FLUENT CFD software. The results produced detailed contour and vector plots of the wingtip vorticity magnitudes created by each wingtip configuration. Results revealed two techniques used by wingtip devices to reduce the wingtip vortices and thus the induced drag on a wing. Winglets exhibited the potential for creating a force component in the direction of an aircraft's thrust, counteracting the drag on the wing. Alternately, raked wingtips displayed a tendency for reducing the overall magnitude of the tip vortices. Although both concepts are aerodynamically beneficial, the raked wingtip is a promising innovation for future use on passenger aircraft.

Back, L. H.

"OPTICAL AND PHYSICAL REQUIREMENTS FOR FLUID PARTICLES MARKING TRAILING VORTICES FROM AIRCRAFT"

Journal of Aircraft, Vol. 13, No. 7, July 1976, pp. 483-489

A theoretical study of the optical and physical requirements of marking trailing vortices that emanate from aircraft wings was carried out by considering particulate light-scattering properties, ability of particles to follow trailing vortices, and survival time of particles to vortex dissipation. Liquid droplets undergoing evaporation and molecular dispersion were investigated. Droplets should have lifetimes of about 300 sec. Droplet size should be about 1 micron to maximize light scattering with the minimum mass of liquid required. Droplets of this small size would spiral outward very slowly and essentially remain in the vortex cores. Nontoxic hygroscopic liquids, having an affinity for moisture in the air, have been identified. These liquids have relatively low vapor pressures of order 10⁻⁵ mm Hg that would ensure droplet persistence long enough to mark trailing vortices.

Backstein, S. and Staufenbiel, R.

"SOME EXPERIMENTAL RESULTS ON SPIRAL VORTEX BREAKDOWN"

Z. Flugwiss Weltraumforsch, Vol. 19, 1995, pp. 359-365

Columnar vortices which are embedded in a flow field with increasing pressure in axial direction tend to vortex breakdown. Moderate adverse pressure gradients induce breakdown in form of a 'spiral' type at free vortices, without neighboring surfaces. To study this phenomenon in detail, experiments were conducted in a water tunnel with a tip vortex stimulated to spiral-type breakdown. For varying pressure gradients continuously and smoothly, a special test setup was developed. The vortex center was visualized by small hydrogen bubbles. By means of flow visualization and LDV measurements, the transition of the slender vortex into a spiral breakdown domain was studied. To analyze the experimental results, a simulation model was developed which permitted to reconstruct vortex structure and center position. It is shown that this type of vortex breakdown is not an abrupt structural change as the 'classical' definition proposes, but more a smooth transformation from one state to another. It is characterized by turning the vortex center into a spiral path, without an essential modification of the vortex structure, before the ordered structure is destroyed by self-induction. Moreover, it can be shown that the appearance of stagnation or reversal of the axial flow, which are stated generally as secondary effects of vortex breakdown, is not an essential feature of spiral breakdown.

Backstein, S. H.

"EXPERIMENTAL AND NUMERICAL RESULTS ON SPIRAL VORTEX BREAKDOWN"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 32-1 to 32-7

Experiments and numerical simulations have been performed to investigate the spiral breakdown of a wing tip vortex in flow fields of adverse axial pressure gradient. The basic idea was to stretch the transition domain by a reduction of the imposed pressure gradient. Embedding the vortex in a flow field with only gradual axial retardation, a stretching could be achieved in both, experiment and calculation, giving some interesting insight into the mechanism of vortex breakdown. The appearance of reversed axial flow, upstream of the spiral, is identified as the distinctive feature of vortex breakdown, that must lead to the loss of axial symmetry and to an unsteady flow.

Baek, K.-H.

"SIMULATIONS OF SHEAR LAYER EFFECTS AND CROW INSTABILITY ON AIRCRAFT WAKE VORTICES"

M.S. Thesis, 1998, University of South Alabama, Mobile, AL

Effects of shear layers on aircraft wake vortices are numerically studied, using a two-dimensional point vortex model. It is found that the mechanism responsible for the asymmetric behaviors of a wake vortex pair can be deduced from inviscid interactions with shear layers. On the other hand, atmospheric turbulence can have effects on the decay of wake vortices by inducing vortex instabilities. Viscous effects on Crow (or sinusoidal) instability are investigated for three-dimensional wake vortices with initial disturbances and axial velocities at the center of vortices. Simulation results suggest that viscous effects tend to decrease the unstable wavelength from Crow's inviscid stability criteria. It is also addressed that the presence of the axial velocities uniquely developed in flow fields during the instability process can decrease the vortex strength at some degree.

Baffico, M. and Lund, F.

"MULTIPLE SCATTERING OF ULTRASONIC WAVES BY SLENDER VORTICES"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

The propagation of ultrasound through a flow that is made up of many slender, randomly distributed vortices, is studied in a multiple scattering approximation. Effective medium equations are derived. They yield an effective speed of sound, as well as an attenuation length. As an example, these quantities are explicitly calculated when the vortices are vortex rings.

Bagai, A. and Leishman, J. G.

"FLOW VISUALIZATION OF COMPRESSIBLE VORTEX STRUCTURES USING DENSITY GRADIENT TECHNIQUES"

Experiments in Fluids, Vol. 15, 1993, pp. 431-442

Mathematical results are derived for the schlieren and shadowgraph contrast variation due to the refraction of light rays passing through two-dimensional compressible vortices with viscous cores. Both standard and small-disturbance solutions are obtained. It is shown that schlieren and shadowgraph

produce substantially different contrast profiles. Further, the shadowgraph contrast variation is shown to be very sensitive to the vortex velocity profile and is also dependent on the location of the peak peripheral velocity (viscous core radius). The computed results are compared to actual contrast measurements made for rotor tip vortices using the shadowgraph flow visualization technique. The work helps to clarify the relationships between the observed contrast and the structure of vortical structures in density gradient based flow visualization experiments.

Bagai, A. and Leishman, J. G.

"ROTOR FREE-WAKE MODELING USING A PSEUDOIMPLICIT RELAXATION ALGORITHM"

J. Aircraft, Vol. 32, No. 6, November-December 1995, pp. 1276-1285

A pseudo-implicit predictor-corrector relaxation algorithm with five-point central differencing in space has been developed for the solution of the governing differential equations of the helicopter rotor free-wake problem. This new approach is compared and contrasted with more conventional explicit-type free-wake algorithms. A convergence analysis shows that the new algorithm provides for much more rapid convergence characteristics compared to explicit methods, with improvements in numerical efficiency and predictive accuracy.

Baggaley, A. W. and Barenghi, C. F.

"TURBULENT CASCADE OF KELVIN WAVES ON VORTEX FILAMENTS"

Journal of Physics, Conference Series, Vol. 318, 13th European Turbulence Conference, 2011, p. 062001.

By numerically integrating in time the motion of vortex filaments, we study how the nonlinear interaction of Kelvin waves along vortices generates Kelvin waves of larger and larger wavenumbers (smaller and smaller wavelength). At sufficiently large wavenumbers the angular velocity of the vortices is large enough that kinetic energy is lost by sound emission. This turbulent cascade of Kelvin waves should explain why turbulence, generated in superfluid helium at very low temperature near absolute zero, quickly decays, despite the lack of any viscous dissipation.

Baggs, C.

"THE WAKE VORTEX REPORTING PROGRAMME: A BRIEF HISTORY AND EXPLANATION OF INCIDENT REPORTING AND DATA CAPTURE"

ATCEU Memorandum No. 177, July 1991, Air Traffic Control Evaluation Unit, National Air Traffic Services, Christchurch, Dorset, UK

This memorandum describes the wake vortex incident database which has been established at the ATCEU since October 1989. It provides an overview of the procedures used for capturing and recording

data from reported wake vortex incidents. Statistical data will be extracted from the database at regular intervals.

Baggs, C.

"THE WAKE VORTEX REPORTING PROGRAMME: ANALYSIS OF INCIDENTS REPORTED BETWEEN JANUARY 1990 AND DECEMBER 1991"

ATCEU Memorandum No. 184, June 1992, Air Traffic Control Evaluation Unit, National Air Traffic Services, Christchurch, Dorset, UK.

This memorandum provides a statistical review of wake vortex incidents which were reported to the ATCEU in the period January 1990 to December 1991. A total of 86 incidents were reported in 1990 and a total of 87 incidents were reported in 1991. The memorandum also summarizes the methods used for capturing and analyzing such data.

Bai, J., Sun, Z., Dong, J. and Huang, J.

"AFTERBODY AERODYNAMIC OPTIMIZATION DESIGN OF TRANSPORT AIRPLANE CONSIDERING WING WAKE FLOW"

Acta Aerodynamica Sinica, Vo. 33, No. 1, February 2015, pp. 134-141.

The aerodynamic optimization design of typical transport afterbody considering the influence of the wing wake flow is studied. An optimization framework is established for the aircraft configuration and used for afterbody optimization at cruising status. The objective of this framework is to optimize the afterbody considering the influence from other parts of aircraft and the engineering constraints simultaneously. The spatial property of the afterbody in spatial control frame is established by implementing the free form deformation (FFD) approach. The NURBS spline is chosen as the basis function, which can represent the property of spatial control element and is suitable for afterbody geometry. Infinite interpolation deforming grid technique is adopted to update spatial grid with high efficiency and mesh quality. The modified Kriging surrogate model and quantum particle swarm algorithm are included in the optimization system to increase efficiency and ability to find global optimal solution. To reduce drag at cruising status, unswept angle and cross section shape are optimized as the main afterbody configuration parameters. The result of the case shows that the aerodynamic performance of the transport's body is improved after the optimization.

Bailey, D. H., Krasny, R. and Pelz R.

"MULTIPLE PRECISION, MULTIPLE PROCESSOR VORTEX SHEET ROLL-UP COMPUTATION"

RNR-92-028, October 1992, NASA Ames Research Center, Moffett Field, CA

This paper describes a vortex sheet roll-up computation using multiple precision arithmetic on a highly parallel computer (an Intel iPSC/860).

Bailey, Jr., W. H. and Durham, T. A.

"AIRCRAFT WAKE INVESTIGATION"

Journal of Aircraft, Vol. 18, No. 2, February 1981, pp. 67-68

The Air Force Weapons Laboratory conducted a test to determine the wake characteristics of a B-52 in flight. Variations in the ambient atmosphere introduced by an aircraft wake manifested by increased wind velocities and gas constituents can cause fluctuations in laser beam propagation. By flying a B-52 upwind of a highly instrumented meteorological tower, wake vortex wind speeds and gas concentrations of the exhausts were obtained. The test was conducted in crosswinds as high as 80 ft/s which allowed the inspection of wakes 5 s in age and 2000 ft behind the aircraft. In this region it was found that the vortex contained: 1) wind speeds more than 210 ft/s and 2) a 250% increase in the concentrations of CO₂. The implication of these results is that propagation of high-energy lasers through aircraft wakes could be seriously degraded.

Bailey, Jr., W. H. and Durham, T. A.

"B-52 WAKE INVESTIGATION"

LOG-C3932, March 1980, Air Force Academy, Colorado Springs, CO

The wake characteristics of a B-52 in flight are determined. Of specific concern is the fact that variations in the ambient atmosphere introduced by an aircraft wake manifested by increased wind velocities and gas constituents can cause fluctuations in laser beam propagation. By flying a B-52 upwind of a highly instrumented meteorological tower, wake vortex wind speeds and gas concentrations of the exhaust were obtained. The test was conducted in crosswinds as high as 80 ft/sec which allowed the inspection of wakes 5 seconds in age and 2000 feet behind the aircraft. In this region, it was found that the vortex contained: (1) wind speeds more than 210 ft/sec and (2) a 250 percent increase in the concentrations of CO₂. The implication of these results is that propagation of high energy lasers through aircraft wakes could be seriously degraded.

Bailey, Jr., W. H., Durham, T. A. and Start, G. E.

"B-52 TOWER FLYBY"

AFWL-TR-78-162, April 1979, Air Force Weapons Lab., Kirtland AFB, NM

A tower flyby test was conducted to determine the wake characteristics of the B-52 bomber. Such information was required for Air Force Weapons Laboratory studies on laser beam propagation. Of particular interest were wake velocities, engine exhaust composition and general wake geometry. The approach was to fly a B-52 crosswind and upstream of an instrumented tower. Measurements were then made as the wake was transported through the tower by the crosswind -- its magnitude, direction

and chemical composition -- together with the flight trajectory of the airplane then allows a spatial sampling of the wake. In addition, a series of flow visualization runs were made using tower and airplane smoke to characterize wake geometry. Crosswinds on the order of 80 feet per second allowed penetrations as close as 2000 feet behind the aircraft. Peak wake velocities of 210 feet per second and CO₂ exhaust concentrations of 250 percent above the ambient condition were recorded.

Bailey, S. C. C. and Tavoularis, S.

"MEASUREMENTS OF THE VELOCITY FIELD OF A WING-TIP VORTEX, WANDERING IN GRID TURBULENCE"

J. Fluid Mech., Vol. 601, 2008, pp. 281-31.

Velocity measurements were performed in a wing-tip vortex wandering in free-stream turbulence using two four-wire hot-wire probes. Vortex wandering was well represented by a bi-normal probability density with increasing free-stream turbulence resulting in increased amplitude of wandering. The most dominant wavelength of wandering was found to remain unaffected by free-stream conditions. Two-point velocity measurements were used to reconstruct the vortex velocity profile in a frame of reference wandering with the vortex. Increasing turbulence intensity was found to increase the rate of decay of the vortex peak circumferential velocity while the radial location of this peak velocity remained unchanged. These results are consistent with several possible decay mechanisms, including the stripping of vorticity by azimuthally aligned vortical structures, transfer of angular momentum from the vortex to these structures during their formation and the deformation and breakup of the vortex by strong free-stream eddies.

Bailey, S. C. C., Tavoularis, S. and Lee, B. H. K.

"EFFECTS OF FREESTREAM TURBULENCE ON WING-TIP VORTEX FORMATION AND NEAR FIELD"

Journal of Aircraft, Vol. 43, No. 5, September-October 2006, pp. 1282-1291.

The formation and near-field development of a wing-tip vortex under the influence of freestream turbulence were examined using flow visualization and hot-wire anemometry. A low turbulence freestream as well as two cases of grid turbulence with different intensities and length scales were considered. In all cases the tip vortex was found to form from three smaller vortices, but the turbulence in its core was found to intensify with increasing freestream turbulence. The vortex trajectory was found to be unaffected by freestream turbulence, but the wing wake that was rolling up around the vortex was observed to have a curvature that decreased as freestream turbulence increased. The mean axial velocity distribution in the low-turbulence case was neither jet-like nor wake-like but had an annular shape. Time-averaged velocity profiles measured in the turbulent freestream cases were wake-like, and it was inferred that the instantaneous profiles would be significantly affected by vortex meandering. Mean circumferential velocity distributions in the vortex core displayed self-similar developments in all cases examined. Finally, it was found that the apparent diffusion in the shear layer shed from the wing increased with increasing freestream turbulence.

Bailey, T. G., Belano, III, J. C., Beran, P. S., Kloeber, Jr., J. M. and Petry, H. J.

"OBJECT-ORIENTED SIMULATION OF PARATROOPER-VORTEX INTERACTIONS"

Proceedings of the Winter Simulation Conference, 1997, pp. 903-910.

The C-17 Airdrop Model provides the Air Force and Army test and evaluation community with the capability to (i) assess the risk of vortex encounters, and (ii) predict ground dispersal patterns on the drop zone. Written in MODSIM III, aircraft vortices and paratroopers are modeled as objects whose behavior accurately reflects their real-world counterparts using pre-validated aerodynamic and trajectory equations within the objects' methods. This model has provided the joint airborne community with a preliminary estimate of paratrooper/vortex encounter rates and locations as a function of formation element separation and wind conditions, as well as a tool for simulating alternative C-17 aircraft formation configurations prior to actual flight. Future use of the model suggests simulating brigade-size operations; expanding to include equipment drops, new parachute deployment systems, and precision airdrop visualization; and, evaluating new airborne combat tactics.

Bajer, K. and Moffatt, H. K.

"THEORY OF NON-AXISYMMETRIC BURGERS VORTEX WITH ARBITRARY REYNOLDS NUMBER"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany, pp. 193-202.

We develop an asymptotic theory of the steady state of a rectilinear vortex in linear straining flow. In the special case of axisymmetric strain, the solution is the familiar Burgers vortex. In the more general non-axisymmetric situation, the asymptotic theories were developed for low Reynolds number (Robinson and Saffman 1984) and for high Reynolds number (Moffatt, Kida and Ohkitani 1994). In the present paper we develop a new expansion in the parameter λ which characterizes the departure from axisymmetry. Hence we obtain an expansion valid uniformly for all Reynolds numbers and thus bridging the gap between the low and the high Reynolds number theories. In practice the new expansion is useful when the non-axisymmetric deformation of the vortex is not too large.

Bajer, K., Bassom, A. P. and Gilbert, A. D.

"VORTEX MOTION IN A WEAK BACKGROUND SHEAR FLOW"

J. Fluid Mech., Vol. 509, 2004, pp. 281-304

A point vortex is introduced into a weak background vorticity gradient at finite Reynolds number. As the vortex spreads viscously so the background vorticity becomes wrapped around it, leading to enhanced diffusion of vorticity, but also giving feedback on the vortex and causing it to move. This is investigated in the linear approximation, using a similarity solution for the advection of weak vorticity around the vortex, at finite and infinite Reynolds number. A logarithmic divergence in the far field

requires the introduction of an outer length scale and asymptotic matching. In this way results are obtained for the motion of a vortex in a weak vorticity field modulated on the large scale and these are confirmed by means of numerical simulations.

Baker, G. R.

"ROLL UP OF A VORTEX SHEET USING THE 'CLOUD-IN-CELL' TECHNIQUE"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 124-13.

The problem of the roll up of a two-dimensional vortex sheet generated by a wing in an ideal fluid is phrased in terms of the stream function and the vortex sheet strength. A numerical method is used to calculate the time evolution of the vortex sheet by adapting the 'Cloud-In-Cell' technique introduced in solving many particle simulations in plasma physics. Two cases are considered for the initial distribution of circulation, one corresponding to an elliptically loaded wing and the other simulating the wing with a flap deployed. Results indicate that small scale behavior plays an important part in the roll up. Typically, the small-scale perturbations evolve into ever increasing larger structures by vortex amalgamation. Conclusions are given from several tests exploring the validity of the method. Briefly, small scale perturbations are introduced artificially by the grid, but the emerging large-scale behavior is relatively insensitive to it. Since clearly defined structures result from the application of this method, it promises to aid considerably in understanding the behavior of vortex wakes.

Baker, G. R. and Pham, L. D.

"A COMPARISON OF BLOB METHODS FOR VORTEX SHEET ROLL-UP"

J. Fluid Mech., Vol. 547, Jan. 2006, pp. 297-316

The motion of vortex sheets is susceptible to the onset of the Kelvin-Helmholz instability. There is now a large body of evidence that the instability leads to the formation of a curvature singularity in finite time. Vortex blob methods provide a regularization for the motion of vortex sheets. Instead of forming a curvature singularity in finite time, the curves generated by vortex blob methods form spirals. Theory states that these spirals will converge to a classical weak solution of the Euler equations as the blob size vanishes. This theory assumes that the blob method is the result of a convolution of the sheet velocity with an appropriate choice of a smoothing function. We consider four different blob methods, two resulting from appropriate choices of smoothing functions and two not. Numerical results indicate that the curves generated by these methods form different spirals, but all approach the same weak limit as the blob size vanishes. By scaling distances and time appropriately with blob size, the family of spirals generated by different blob sizes collapse almost perfectly to a single spiral. This observation is the next step in developing an asymptotic theory to describe the nature of the weak solution in detail.

Baker, G. R., Barker, S. J., Bofah, K. K. and Saffman, P.G.

"LASER ANEMOMETER MEASUREMENTS OF TRAILING VORTICES IN WATER"

J. Fluid Mech., Vol. 65, Part 2, August 1974, pp. 325-336

A series of measurements of trailing vortices behind lifting hydrofoils is described. These measurements were made in the Caltech Free-Surface Water Tunnel, using a laser-Doppler velocimeter to measure two components of velocity in the vortex wake. Two different model planforms were tested, and measurements were made at several free-stream velocities and angles of attack for each. Velocity profiles were measured at distances downstream of the model of from five to sixty chord lengths. The theory of trailing vortices is discussed. The effects of 'vortex wandering' upon the measurements are computed, and the corrected results are seen to be in reasonable agreement with the theory.

Balcerak, J. C. and Zalay, A. D.

"INVESTIGATION OF THE EFFECTS OF MASS INJECTION TO RESTRUCTURE A TRAILING TIP VORTEX AT TRANSONIC SPEEDS"

RASA-73-03M, February 1973, Rochester Applied Science Assoc., Rochester, NY

This report describes the results of an experimental research program which was conducted to assess the effects of mass injection in the tip vortex on airfoil performance in transonic flow. Balance data and Schlieren photographs were taken for a rectangular semispan model with a full-span aspect ratio of 7.35 in the Mach number range of 0.553 to 1.0. The results of the investigation indicates that mass injection of the concentrated tip vortex does not generate any significant change in airfoil performance at transonic speeds for the configuration tested. Schlieren photographs of the compressible flow field showed that the near field flow characteristics of the airfoil were not influenced by mass injection or by passive nozzle characteristics at transonic speeds.

Baldacchino, D. and van Bussel, G. J. W.

"WIND TURBINE WAKE STABILITY INVESTIGATIONS USING A VORTEX RING MODELLING APPROACH"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012111-1 - 012111-10.

In the present study, a simple inviscid vortex ring (VR) modelling approach is used to represent the developing rotor wake. This allows a straightforward investigation and comparison of the impact of uniform, yawed and sheared flow conditions on the development of the rotor wake, with the additional possibility of including ground effect. The effect of instabilities on the development of the wake is manually introduced in the form of perturbations of strength, ring position and size. The phenomenon of vortex filament interaction or leapfrogging could play a role in the observation of unsteady phenomena and is therefore also addressed. Such a study is hence performed considering recent conflicting views on the causes of wake meandering: is the observed dynamic wake behavior a result of large-scale turbulent forcing or do more subtle and intrinsic wake instabilities play a role? This study

concludes that the presence of the ground and external perturbations, most notably changes in the wake pitch and the rotor thrust coefficient, can significantly affect the steady development of the wake. The mutual vortex pairing instability, whilst displaying interesting periodic behavior, does not correlate with periodic wake behavior reported by Medici et al. However, in the absence of unsteady inflow, it is shown that the wake of a Horizontal Axis Wind Turbine (HAWT) is certainly prone to displaying unstable, dynamic behavior caused by these additional factors.

Baldwin, B. S., Chigier, N. A. and Sheaffer, Y. S.

"DECAY OF FAR FLOW FIELD IN TRAILING VORTICES"

NASA TN-D-7568, February 1974, NASA Ames Research Center, Moffett Field, CA

A finite difference machine code is used in the wake vortex problems in the quasi-cylindrical boundary layer approximation. A turbulent energy model containing new features is developed that accounts for the major effects disclosed by more advanced models in which the parameters are not yet established. Several puzzles that arose in previous theoretical investigations of wake vortices are resolved.

Baldwin, B. S., Chigier, N. A. and Sheaffer, Y. S.

"DECAY OF FAR-FLOWFIELD IN TRAILING VORTICES"

AIAA Journal, Vol. 11, No. 12, December 1973, pp. 1601-1602

Methods for reduction of velocities in trailing vortices of large aircraft are of current interest; finite-difference calculations of the flow in turbulent wake vortices were done as an aid to interpretation of wind-tunnel and flight experiments directed toward that end.

Baldwin, B. S., Sheaffer, Y. S. and Chigier, N. A.

"PREDICTION OF FAR FLOW FIELD IN TRAILING VORTICES"

AIAA Paper No. 1972-0989, Palo Alto, CA, 1972

A finite-difference machine code is brought to bear on the wake-vortex problem in the quasi-cylindrical boundary-layer approximation. A turbulent-energy model containing new features is developed. Parameters of the model are evaluated by comparison of calculated velocities and turbulent intensities with measurements in an axisymmetric wake. Comparisons are made with a previous calculation of the decay of an isolated vortex and with wind tunnel and flight measurements in trailing vortices. A self-similar solution develops at large axial distance that decays with the square root of distance. A slower decay occurs in the preceding transition region.

Ball, C. T.

"CHICAGO O'HARE INTERNATIONAL AIRPORT CAPACITY ANALYSIS"

FAA-RD-75-205, November 1975, Federal Aviation Administration, Washington, DC.

A task force comprised of representatives from the FAA, airlines, and the City of Chicago was formed in December of 1974 to study the present and future capacity and delay of the Chicago O'Hare International Airport. The task force effort concentrated on two future air traffic control environments: One consisting of basic metering and spacing and wake, one consisting of basic metering and spacing and a wake vortex predictive system; the other consisting of advance metering and spacing, a discrete address beacon system, and a wake vortex predictive system. January 1975 schedule information was used to determine the present future capacity of the airport.

Ballish, B. A. and Kumar, V. K.

"SYSTEMATIC DIFFERENCES IN AIRCRAFT AND RADIOSONDE TEMPERATURES"

Bulletin American Meteorological Society, November 2008, pp. 1689-1708.

Automated aircraft temperatures exhibit considerable variance with aircraft models and on average they are warmer than radiosonde temperatures; therefore, field studies and bias corrections for NWP models are recommended.

Balmforth, N. J., Smith, S. L. and Young, W. R.

"DISTURBING VORTICES"

Journal of Fluid Mechanics, Vol. 426, 2001, pp. 95-133.

Inviscid spatially compact vortices (such as the Rankine vortex) have discrete Kelvin modes. For these modes, the critical radius, at which the rotation frequency of the wave matches the angular velocity of the fluid, lies outside the vortex core. When such a vortex is not perfectly compact, but has a weak vorticity distribution beyond the core, these Kelvin disturbances are singular at the critical radius and become 'quasi-modes'. These are not true eigenmodes but have stream function perturbations that decay exponentially with time while the associated vorticity wraps up into a tight spiral without decay. We use a matched asymptotic expansion to derive a simplified description of weakly nonlinear, externally forced quasi-modes. We consider the excitation and subsequent evolution of finite-amplitude quasi-modes excited with azimuthal wavenumber 2. Provided the forcing amplitude is below a certain critical amplitude, the quasi-mode decays and the disturbed vortex returns to axisymmetry. If the amplitude of the forcing is above critical, then nonlinear effects arrest the decay and cat's eye patterns form. Thus the vortex is permanently deformed into a tripolar structure.

Balser, M., McNary, C. A. and Nagy, A. E.

"ACOUSTIC ANALYSIS OF AIRCRAFT VORTEX CHARACTERISTICS"

FAA-RD-72-81, July 1972, Xonics Inc., Van Nuys, CA

A program of field measurements at NAFEC and related analysis has been carried out as part of the development of acoustic radar for aircraft vortex turbulence detection. Spectra of acoustic signals scattered from the vortices were found to agree in form with those derived from a model, and yielded velocities that generally agreed with those observed by the NAFEC tower instrumentation. Consistent quantitative measurements of circulation, the quantity most closely related to hazard, were obtained for several different aircraft. Confident vortex tracks were obtained for aircraft (a DC-6) altitudes up to 1500 ft, with the vortex detected at about 1300 ft and tracked for about a minute until it passed out of the coverage region.

Balser, M., McNary, C. A. and Nagy, A. E.

"ACOUSTIC BACKSCATTER RADAR SYSTEM FOR TRACKING AIRCRAFT TRAILING VORTICES"

Journal of Aircraft, Vol. 11, No. 9, September 1974, pp. 556-562

The safety hazard posed by potential encounters with invisible vortices from preceding aircraft imposes stringent limitations on aircraft spacing in the terminal area, hence on traffic-handling capacity. An acoustic back-scatter radar system has been developed to detect and track such vortices, and thereby provide the information for more advanced air traffic procedures that would eliminate the uncertainty and delay caused by vortices. The system is fully engineered and operates in real time. Examples of the real-time display and of vortex tracks from Boeing 747's landing at the Los Angeles International Airport are given in the paper.

Balser, M., Nagy, A. E. and Proudian, A. P.

"VORTEX OBSERVATIONS BY THE XONICS ACOUSTIC RADAR AT NAFEC"

FAA-RD-71-103, December 1971, Xonics Inc., Van Nuys, CA

A series of flight tests was conducted in order to demonstrate feasibility of the concept of the Xonics acoustic vortex detector. The first tests consisted of simultaneous observations in close proximity by both the Xonics equipment and the instrumented tower of vortices shed by a low-flying aircraft. Except for the few cases where data was lost through equipment misalignment or malfunction or operator error, vortex returns were observed on virtually all of the runs. A total of 55 runs, which represents a substantial fraction of all the data gathered, were selected for analysis. The vortex velocity measurements exhibit a clear correlation with aircraft configuration, and appear to confirm their use as a valid indicator of vortex intensity.

Balser, M., Nagy, A. E. and Proudian, A. P.

"AIRCRAFT VORTEX DETECTION SYSTEM"

US Patent 3,735,333, May 1973

An improved system for detection and measurement of aircraft wing tip vortices over a wide area. An acoustic echo system with transmitter and receiver spaced from each other in a plane perpendicular to the flight path for illuminating the vortex and picking up scattering of the transmitter signal produced by the vortex, using Doppler frequency spectrum analysis with the maximum and minimum frequencies providing measure of vortex intensity. A plurality of receivers operating with a common transmitter providing coverage of an area of interest along a flight path. A transmitter covering a broad area by a broad beam acoustic transducer or a plurality of narrow beams, and means for identifying a specific zone within the broad area occupied by the vortex being analyzed.

Banakh, V. A, and Smalikho, I. N.

"AIRCRAFT WAKE VORTEX PARAMETRIZATION BASED ON 1.5-MICRON COHERENT DOPPLER LIDAR DATA"

27th ILRC International Laser Radar Conf., July 2015, New York City, NY.

A strategy of measurement by a 1.5-micron pulsed coherent Doppler lidar 'Stream Line' has been developed, and a method for estimation of aircraft wake vortices from the lidar data has been proposed. The principal possibility of obtaining the information about the vortex situation over an airport airfield with the Stream Line lidar has been demonstrated.

Banakh, V. A. and Smalikho, I. N.

"ESTIMATION OF THE TURBULENCE ENERGY DISSIPATION RATE FROM THE PULSED DOPPLER LIDAR DATA"

Atmospheric and Oceanic Optics, Vol. 10, No. 12, December 1997, pp. 957-965.

Based on the results of numerical modeling we have analyzed the possibility and calculated the errors of estimating turbulence kinetic energy dissipation rate from data of pulsed Doppler lidar. Compared are the accuracies of estimation of wind velocity spatial structure function from Doppler lidar data obtained by the method of correlation function argument and the method of maximum likelihood. It is shown that, when using sufficiently large number of sample data, the relative error in estimation of turbulence energy dissipation rate with a pulsed Doppler lidar must be below 15-20 percent at signal-to-noise ratio equal or greater than unity.

Banakh, V. A., Brewer, A., Pichugina, E. L. and Smalikho, I. N.

"MEASUREMENTS OF WIND VELOCITY AND DIRECTION WITH COHERENT DOPPLER LIDAR IN CONDITIONS OF A WEAK ECHO SIGNAL"

Atmospheric and Oceanic Optics, Vol. 23, No. 5, 2010, pp. 381-388.

The possibility of measuring the wind velocity and direction with 2-micron pulsed coherent Doppler lidar in conditions of a weak echo signal is investigated. It is shown that the use of the filtered sine wave fitting of the lidar-measured radial wind velocities allows for the estimation of the wind velocity vector components with an acceptable accuracy at a low signal-to-noise ratio up to values of -20 dB.

Banakh, V. A., Smalikho, I. N. and Falits, A. V.

"ESTIMATION OF THE TURBULENCE ENERGY DISSIPATION RATE IN THE ATMOSPHERIC BOUNDARY LAYER FROM MEASUREMENTS OF THE RADIAL WIND VELOCITY BY MICROPULSE COHERENT DOPPLER LIDAR"

Optics Express, Vol. 25, No. 19, September 2017, pp. 22679-22692.

The accuracy of the method of azimuth structure function for estimation of the dissipation rate of the kinetic energy of turbulence from an array of radial velocities measured by low-energy micropulse coherent Doppler lidars with conical scanning by a probing beam around the vertical axis has been studied numerically. The applicability of the method in dependence on the turbulence intensity and the signal-to-noise ratio has been determined. The method of azimuth structure function was applied for estimation of the turbulent energy dissipation rate from radial velocities measured by the lidar in the experiments on the coast of Lake Baikal. Two-dimensional time-height patterns of the wind turbulence energy dissipation rate were obtained. Part of them were obtained in presence of the atmospheric internal waves (AIWs) and low-level jet streams. It is observed that the wind turbulence in the area occupied by jet streams is very weak. In the process of dissipation of AIWs the wind turbulence strength increases.

Banakh, V. A., Smalikho, I. N., Pichugina, E. L. and Brewer, W. A.

"REPRESENTATIVENESS OF MEASUREMENTS OF THE DISSIPATION RATE OF TURBULENCE ENERGY BY SCANNING DOPPLER LIDAR"

Atmospheric and Oceanic Optics, Vol. 23, No. 1, 2010, pp. 48-54.

The representativeness of measurements of the dissipation rate of atmospheric turbulence energy by 2-micron pulsed coherent Doppler lidar scanning in the vertical plane is studied experimentally. A comparison of the results of simultaneous measurements of the dissipation rate at different altitudes in the atmospheric boundary layer by lidar and four sonic anemometers has shown that the lidar estimate has a small bias and its relative error does not exceed 25 percent.

Banakh, V. A., Smalikho, I. N., Pichugina, Y. L. and Brewer, W. A.

"ESTIMATION OF THE TURBULENCE ENERGY DISSIPATION RATE FROM THE PULSED COHERENT DOPPLER LIDAR DATA MEASURED AT THE CONICAL SCANNING"

9th International Symposium on Tropospheric Profiling (ISTP), September 2012, University of L'Aquila, L'Aquila, Italy.

In this paper we present the basic relations for the estimation of the turbulence energy dissipation rate from the transverse and longitudinal structure function of the radial wind velocity measured by pulsed coherent Doppler lidar (CDL) at the conical scanning (both one full scan and multiple sectorial scanning). We compare the results of the pulsed CDL profiling the dissipation rate in the ABL by these methods with the estimation of the dissipation rate obtained from the sonic anemometer data. We present the results of estimating the dissipation rate at the given height from the transverse and from the longitudinal structure function calculated based on the same data of the radial wind velocity measured by CDL during long temporal period and compare these results with each other.

Bandyopadhyay, P. R., Stead, D. J. and Ash, R. L.

"ORGANIZED NATURE OF A TURBULENT TRAILING VORTEX"

AIAA Journal, Vol. 29, No. 10, October 1991, pp. 1627-1633

Experiments have been carried out into the turbulence structure of a low-Reynolds-number trailing vortex produced at the juncture of a flow aligned cylinder and a pair of oppositely loaded airfoils. Five different types of screens are placed ahead of the vortex generator. Components of the mean velocity, Reynolds stress flux, and quasiperiodic large-scale wavelengths have been measured. The turbulence structure varies with Rossby number. The vortex core is not a benign solid body of rotation. It has intermittent patches of turbulent and laminar fluid. The shear-stress-rich low-momentum core fluid intermittently ejects outwards in the direction of vortex rotation.

Banta, R. M., Pichugina, Y. L., Brewer, W. A., Lundquist, J. K., Kelley, N. D., Sandberg, S. P., Alvarez II, R. J., Hardesty, R. M. and Weickmann, A. M.

"3D VOLUMETRIC ANALYSIS OF WIND TURBINE WAKE PROPERTIES IN THE ATMOSPHERE USING HIGH-RESOLUTION DOPPLER LIDAR"

Journal of Atmospheric and Oceanic Technology, Vol. 32, 2015, pp. 904-914.

Wind turbine wakes in the atmosphere are three-dimensional (3D) and time dependent. An important question is how best to measure atmospheric wake properties, both for characterizing these properties observationally and for verification of numerical, conceptual, and physical (e.g., wind tunnel) models of wakes. Here a scanning, pulsed, coherent Doppler lidar is used to sample a turbine wake using 3D volume scan patterns that envelop the wake and simultaneously measure the inflow profile. The volume data are analyzed for quantities of interest, such as peak velocity deficit, downwind variability of the deficit, and downwind extent of the wake, in a manner that preserves the measured data. For the case study presented here, in which the wake was well defined in the lidar data, peak deficits of up to 80 percent were measured 0.6-2 rotor diameters (D) downwind of the turbine, and the wakes extended more than 11D downwind. Temporal wake variability over periods of minutes and the effects of atmospheric gusts and luffs in the inflow are demonstrated in the analysis. Lidar scanning trade-offs important to ensuring that the wake quantities of interest are adequately sampled by the

scan pattern, including scan coverage, number of scans per volume, data resolution, and scan-cycle repeat interval, are discussed.

Bao, F. and Vollmers, H.

"ALLEVIATION OF END-EFFECT IN FACILITIES FOR FAR WAKE INVESTIGATIONS"

AIAA Paper No. 2005-0907, Reno, NV, January 2005

This paper deals with the end-effect problem encountered in the wake vortex researches in test facilities with limited length. The disturbances produced during the launching and recovering of a/c models may propagate along the vortex core and introduce a helical instability which will burst off the vortex core. When the disturbances reach the measurement region, the results will be spoiled. Investigations were made in a water towing tank, which was instrumented with a stereo PIV system and visualization devices. Methods for alleviating the end-effect were studied and one effective setup was patented.

Bao, F., Liu, J., Zhu, H., Jiang, J. and Wang, J.

"CONTROL METHOD FOR AIRCRAFT WAKE VORTEX BASED ON RAYLEIGH-LUDWIG INSTABILITY"

Journal of Beijing University of Aeronautics and Astronautics, Vol. 41, No. 8, August 2015, pp. 1381-1387.

The aircraft wake vortex is an inherent flow phenomenon due to the lift generation mechanism, which has a negative impact on the flight safety. By adding a set of specially designed spoiler, a rectangular wing was designed to generate a pair of weaker vortices, which had different sizes and opposite direction compared to main wing vortices, thereby constructing a self-destructive four-vortex wake system to induce Rayleigh-Ludwig instability. Under different experimental conditions, in terms of changing the size or shape of the spoiler, towing speed and angle of attack, the wake vortex development of the test model, that both with and without spoiler, as well as the circulation analysis, were acquired particle image velocimetry (PIV) measurements under the Reynolds number. The study demonstrates that the decrease in circulation was 35 percent to 55 percent in 45 wingspans when spoilers are introduced, whereas the counterpart of the baseline airfoil, without spoilers, is nearly kept steadily, which reveal the application possibility of Rayleigh-Ludwig instability in alleviating the wake vortex. As the initial circulation ratio equals to -0.489 and the initial distance ratio is 0.5, the circulation of the primary vortex reduces most significantly (55.9 percent) in 45 wingspans. Results would provide a scheme in the design of airfoils with weaker vortices.

Bao, F., Liu, J., Zhu, R. and Liu, Y.

"EXPERIMENTAL STUDY ON RAYLEIGH-LUDWIG INSTABILITY OF AIRCRAFT WAKE VORTEX"

Acta Aeronautica et Astronautica Sinica, Vol. 36, No. 7, July 2015, pp. 2166-2176.

Based on the fact that the main wing and tail would produce counter-rotating vortices in the process of taking-off and landing, a set of double vortex generators are designed. Under two different experimental conditions, in terms of changing the position and initial intensity ratio of the double vortex, the wake vortex development of the test mode is acquired, including flow visualizations and particle image velocimetry (PIV) technology. Research reveals that the introduction of a weaker vortex, with a proper position and initial intensity ratio, would change the main vortex original trajectory and promotes its dissipation. However, it does not present an obvious linear relationship between them. The analysis results of vortex trajectory could be used in improving the efficiency of taking-off and landing in airports, the experiments also provide a reference for the overall design of aircrafts: when the requirement for flight mechanics design is satisfied, optimizing the overall aerodynamic layout will have a significant effect on alleviating the intensity of aircraft wake. [In Chinese.]

Bao, F., Vollmers, H. and Mattner, H.

"EXPERIMENTAL STUDY ON CONTROLLING WAKE VORTEX IN WATER TOWING TANK"

Proceedings 20th International Congress on Instrumentation in Aerospace Simulation Facilities 2003, Gottingen, Germany, August 25-29, 2003, pp. 214-223

An experimental study was carried out to establish a self-destructing vortex wake. Sets of horizontal tail plains were employed to generate additional vortex sheet interacting with the wing vortex sheet of a rectangular wing. The study was made in the water towing tank in Gottingen (WSG), which was instrumented with 2D/3C PIV system, balance and flow visualization devices. The tailoring of 4 vortices wake systems was achieved by varying horizontal tail plains with different aspect ratios with various incidences, generating various destabilizing effects. The study exhibited that the interaction of tail vortices with tip vortices may result in a promising self-destructive mechanism within the wake system in the sense that the vortex core experiences an instability and decay abruptly. Typically, the wake vortex cores could be destabilized by as early as in 30 wing spans downstream with suitable tail settings, instead of more than 100 wing spans for that of a 'clean model'. The possible influence from the finite movement in the water tank due to transient processes of the model (end-effect) was investigated. The influence of the bottom and side wall effects was estimated from comparison of results from a larger water towing tank (HSVA).

Bao, F., Zhu, R., Liu, Z. and He, Y.

"FOUR-VORTEX SYSTEM RECONSTRUCTION AND EXPERIMENTAL STUDY OF ITS WAKE FEATURES"

Acta Aeronautica et Astronautica Sinica, Vol. 36, No. 5, May 2015, pp. 1491-1499.

The aircraft wake vortex is a coherent flow phenomenon due to the lift generation mechanism, which threatens the flight safety and limits airport operation efficiency. By mounting a vortex generator onto the wingtip of a rectangular airfoil, a secondary vortex that rotated reversely to the primary vortex is produced, thereby constructing a self-destructed four-vortex system to accelerate the dissipation of the primary vortex. Combined with flow visualizations and particle image velocimetry (PIV) measurements,

a parametric study of the spatial evolution and vorticity development of the four-vortex system in 25 wingspans, as well as the circulation reduction rate in 45 wingspans, is conducted. The results exhibit that the interaction instability of the wake vortex is triggered by the secondary vortex in advance, resulting in the premature breakdown of the primary vortex, resulting in the decline of its vorticity. As the initial circulation ratio is -0.581 and the initial distance ratio is 0.5, the circulation of the primary vortex is reduced most significantly (34.7%) in 45 wingspans. The results would provide a scheme for the design of airfoils with weaker vortices. [In Chinese.]

Baranov, N. A.

"WAKE VORTEX DYNAMICS STUDY IN TEMPERATURE INVERSION CONDITIONS"

WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation, September 2016, Madrid, Spain.

The presented results have been obtained following numerical modeling of aircraft wake vortex dynamics in the conditions of surface temperature inversion of the atmosphere. Modeling was based on data from surface temperature profile monitoring, which took place in winter and spring at Sochi airport using MTP-5 meteorological temperature profiler. A comparative analysis of the wake vortex dynamics in the absence and presence of a side wind of varying intensity was carried out for a number of temperature inversion cases, such as surface inversion, elevated inversion with different layer altitude inversion, elevated inversion with surface isothermy.

Baranov, N. A. and Turchak, L. I.

"INVESTIGATION OF AIRCRAFT VORTEX WAKE STRUCTURE"

Application of Mathematics in Technical and Natural Sciences, AIP Conference Proceedings, Vol. 1629, 2014, pp. 44-55.

In this work we analyze the mechanisms of formation of the vortex wake structure of aircraft with different wing shape in the plan flying close to or away from the underlying surface cleaned or released mechanization wing.

Baranov, N. A. and Turchak, L. I.

"AIRCRAFT RECATEGORIZATION PRESERVING THE WAKE VORTEX SAFETY"

European Researcher, Vol. 20, No. 5-1, 2012, pp. 436-439.

We formulate the recategorization problem of aircrafts. It is assumed that the partition of aircrafts into categories must provide a specified level of the wake vortex safety. [In Russian.]

Baranov, N. A., Belotserkovski, A. S., Kanevski, M. I. and Pasekunov, I. V.

"METHOD AND SYSTEM FOR PREVENTING AN AIRCRAFT FROM PENETRATING INTO A DANGEROUS TRAILING VORTEX AREA OF A VORTEX GENERATOR"

US Patent 7,333,030 B2, February 2008

The invention relates to methods and devices for aircraft's safe operation and is embodied in the form of a method and system for informing a user, for example an aircraft crew and/or a flight controller, on the probable penetration of the aircraft into dangerous areas of the vortex shedding of vortex generators which are located near the aircraft at a forecast time when the aircraft passes through a simulated control plane situated at a preventive distance in the direction of motion of the aircraft, said distance being calculated on a basis of a sufficient forecast period so that the aircraft carries out a flight evasive maneuver. The preventive system defines the trajectory and intensity of the vortex shedding of the vortex generators, the co-ordinates of intersecting points of the vortex sheddings with a control plane, the geometric parameters of the dangerous areas thereof according to danger criteria specified by a user, forms a warning area in said control plane, an area of the forecast positions of the aircraft and dangerous vortex shedding areas at a forecast time, follows up the events of crossing the warning area and/or the area of the aircraft forecast positions associated with the dangerous vortex shedding areas and draws attention of the user to said event with the aid of display devices and a visualization device.

Baranov, N. A., Belotserkovski, A. S., Kanevski, M. I. and Pasekunov, I. V.

"INTEGRATED SYSTEM FOR AIRCRAFT VORTEX SAFETY"

US Patent Application 2007/0103340 A1, May 2007.

The invention relates to systems for preventing off-normal situations when there is a possibility that an aircraft penetrates a dangerous area of the vortex shedding of a vortex generator. The inventive system consists of information sub-systems for recording and storing information on the expected relative position of the aircraft and trailing vortex areas in line with danger criteria which are specified by a user and concern dangerous aerodynamic forces and torques effecting the aircraft and induced by the trailing vortex of vortex generators, and for conveying said information to said user, who can be the aircraft crew and/or flight attendants, at a preventive distance from the aircraft and at a forecast moment. Said information can be visualized in a human-readable form and in a volume sufficient for forming a directive signal for carrying out a flight maneuver by the aircraft to move away from the dangerous trailing vortex area.

Baranov, N., Petrov, G. and Shiriaev, I.

"WIND SPEED VECTOR RESTORATION ALGORITHM"

28th International Laser Radar Conference, June 2017, Bucharest, Romania, published in EPJ Web of Conferences, Vol. 176, 2018, pp. 06012-1 to 06012-4.

Impulse wind lidar (IWL) signal processing software developed by JSC <<BANS>> recovers full wind speed vector by radial projections and provides wind parameters information up to 2 km distance. Increasing accuracy and speed of wind parameters calculation signal processing technics have been studied in this research. Measurement results of IWL and continuous scanning lidar were compared. Also, IWL data processing modeling results have been analyzed.

Barata, J. M. M., Bernardo, N., Santos, P. J. C. T. and Silva, A. R. R.

"EXPERIMENTAL STUDY OF A GROUND VORTEX: THE EFFECT OF THE CROSSFLOW VELOCITY"

Journal of Aircraft, Vol. 50, No. 1, January-February 2013, pp. 298-302.

Laser-Doppler measurements of the velocity characteristics of a ground vortex flow resulting from the collision of a wall jet with a boundary layer were reported for velocity ratios equal to 0.5 and 0.62. Two secondary vortices were found upstream of the separation point for the highest velocity ratio. These vortical structures affect the interaction zone and the separation point in the wall jet side moves upstream. The angle of deflection of the upwash flow was found to decrease with the velocity ratio. The turbulent structure of the collision zone is not substantially affected by the velocity ratio, but important changes occur above the wall jet for the higher velocity ratio. The flow remains essentially isotropic everywhere except near the separation point.

Barata, J. M. M., Durao, D. F. G., Santos, P. J. C. T. and Silva, A. R. R.

"TURBULENT ENERGY BUDGETS OF A GROUND VORTEX FLOW"

15th International Symposium on Applications of Laser Techniques to Fluid Mechanics, July 2010, Lisbon, Portugal.

Turbulent kinetic energy budgets are presented for a highly curved flow generated by the collision of plane wall turbulent jet with a low-velocity boundary layer. The different terms are obtained in the vertical plane of symmetry by quadratic interpolation of the LDV measurements, for a wall jet-to-boundary layer velocity ratio of 2. The results, which have relevance to flows encountered by powered-lift aircraft operating in ground effect, quantify the structure of the complex ground vortex flow resulting from the collision of a wall jet with a boundary layer. The analysis of turbulent energy equation terms using the measured data revealed that production by normal and shear stresses are both very important to the turbulent structure of the impact zone of the ground vortex. The analysis of turbulent kinetic energy indicates the modeling of turbulence of deflected flow resultant from the collision between the wall jet and the boundary layer this may require an adequate treatment.

Barba, L. A., Leonard, A. and Allen, C. B.

"VORTEX METHOD WITH MESHLESS SPATIAL ADAPTION FOR ACCURATE SIMULATION OF VISCOUS, UNSTEADY VORTICAL FLOWS"

International J. for Numerical Methods in Fluids, Vol. 47, March 2005, pp. 841-84.

A vortex method has been developed where spatial adaption of the Lagrangian vortex particles is provided by the technique of radial basis function interpolation. In this way, the meshless formulation of the vortex method is preserved throughout. Viscous effects are provided by the core spreading method, where core size control is accomplished in the spatial adaption, thus ensuring convergence. Numerical experiments demonstrate considerable increase in accuracy, in comparison with standard remeshing schemes used with vortex methods. Proof-of-concept is achieved successfully on a problem of quasi-steady tripole vortex flow, and parallel implementation of the method has permitted high accuracy computations of vortex interactions at high Reynolds number.

Barbagallo, D., De Gregorio, F. and Tino, N.

"HELICOPTER WAKE INVESTIGATIONS BY MEANS OF PIV AND HW MEASUREMENT TECHNIQUES"

9th International Symposium on Flow Visualization, Paper No. 415, 2000, pp. 415-1 - 415-16

During the first two weeks of November 1998, a measurement campaign was conducted to investigate the reliability of the Particle Image Velocimetry and the Hot Wire Anemometer techniques on high unsteady phenomena in an industrial facility. At the same time the aerodynamics interaction phenomenon occurring between the helicopter rotor and the tailplanes, better known as pitch-up phenomenon, was studied. Time-average and unsteady velocity flow field measurements were carried out at different chordwise stations on different horizontal tailplane positions, for different values of the advance ratio. The results have shown that the PIV can be a powerful tool in the experimental aerodynamics field, especially to investigate high unsteady phenomena. The comparison of the time-averaged velocity field by PIV and HW results have shown good agreement. The pitch-up phenomenon was measured and the advance ratio values relative to the wake impinging on the tailplanes were detected. The main rotor tip vortex has been measured and for some test cases the PIV measurement system was phase locked to the helicopter main rotor in order to investigate the velocity behavior related to the rotor azimuth position.

Barbaresco, F.

"AIRPORT RADAR MONITORING OF WAKE VORTEX IN ALL WEATHER CONDITIONS"

Proceedings of the 7th European Radar Conference, September 2010, Paris, France, pp. 85-88.

To assess maturity and capability of X-band radars to monitor wake roll-ups in all weather conditions, radar data were collected on airports, near runway at Orly airport and just under its ILS Interception Area. Additional trials took place on Paris-CDG Airport to benchmark Lidar and Radar Technologies. Continuous detection, characterization, and profiling capabilities of wake vortices, up to a range of 2000 m, have been proved in clear air and rainy weather. Recorded data have been correlated with electromagnetic and fluid mechanical models of wake turbulences for better and more accurate understanding of roll-ups radar cross section and Doppler signature. X-band radar has been proved to be a full-fledged alternative, which can make a significant contribution to a wake vortex alert system,

but to achieve as much reliability as possible, collaborative electro-optical and electromagnetic sensors solution is envisaged encapsulated in a Wake Vortex Advisory System. These sensors could be used to permanently monitor turbulence on runways.

Barbaresco, F.

"METHOD FOR RADAR MONITORING OF WAKE TURBULENCE"

US Patent Application 2010/0117892 A1, May 2010.

The present invention relates to a method for detecting and grading the state and the evolution of wake turbulence caused by an aircraft, based on the radar signals reflected by this turbulence, these signals being analyzed through analysis cells of given dimension in terms of distance and bearing. This method mainly comprises: a first preliminary detection step proper for detecting and locating turbulence in a cell, a second step for determining the strength of the detected turbulence, and a third step for determining the age of the detected turbulence as well as the geometric parameters which characterize it. The method according to the invention advantageously makes it possible to detect wake turbulence and to determine at one and the same time the position and the strength of the latter as well as its stage of evolution. The invention applies in particular to the field of air traffic control and air safety in general.

Barbaresco, F. and Meier, U.

"RADAR MONITORING OF A WAKE VORTEX: ELECTROMAGNETIC REFLECTION OF WAKE TURBULENCE IN CLEAR AIR"

Comptes Rendus Physique, Vol. 11, 2010, pp. 54-67.

This article deals with X-band radar trial campaigns in 2006 and 2007 at Orly Airport, and in June 2008 at Paris-CDG Airport. An X-band Doppler radar has been deployed to assess short range (inferior to 2000 m) wake vortex monitoring capabilities in all weather conditions (dry and wet conditions). Recorded data have been correlated with electromagnetic and fluid mechanical models of wake turbulence for better and more accurate understanding of roll-up radar cross section and Doppler signature.

Barbaresco, F., Brion, V. and Jeannin, N.

"RADAR WAKE-VORTICES CROSS-SECTION/DOPPLER SIGNATURE CHARACTERISATION BASED ON SIMULATION AND FIELD TEST TRIALS"

IET Radar, Sonar and Navigation, 2015, pp. 1-15.

Runway operation is the limiting factor for the overall throughput of airports. Today the International Civil Aviation Organization (ICAO) imposes wake vortex separation minima between following aircrafts that are based on simple pair-wise rules. However, the lifetime of wake vortices results from a much

broader basis of factors, that ranges from a large set of aircraft parameters to meteorological conditions and traffic mix. In particular, atmospheric conditions can significantly reduce wake hazard, for instance, in case of strong turbulence or crosswinds. While such situations could allow a reduction of the separation minima, safety reasons and the current technical challenges of detecting and managing such scenarios leads to the strict application of the ICAO standards. With the aid of accurate wind data and precise measurements of wake vortices, more efficient intervals could be set, particularly when weather conditions turn unfavorable. Depending on traffic intensity, these adjustments could enhance airport capacity, and generate major commercial benefits. This study deals with recent development in the radar technology to attain such goals. It presents (i) the trials of an electronic scanning radar to be used in a future wake turbulence advisory system and (ii) theoretical and numerical analysis of the radar response in clear air and in rainy weather. Part of this work has been achieved with the support of the European ATM research program SESAR.

Barbaresco, F., Brovelli, P., Currier, P., Garrouste, O., Klein, M., Juge, P., Ricci, Y. and Schneider, J.-Y.

"RADAR SENSORS FOR WIND & WAKE-VORTEX MONITORING ON AIRPORT: FIRST RESULTS OF SESAR P12.2.2 XPO TRIALS CAMPAIGN AT PARIS CDG AIRPORT"

7th European Conference on Radar in Meteorology and Hydrology (ERAD), June 2012, Toulouse, France.

This paper will present European SESAR P12.2.2 project that develops a verified wake turbulence system according to related operational concept improvements to, punctually or permanently, reduce landing and departure wake turbulence separations and, therefore, to increase the runway throughput in such a way that it safely absorbs arrival demand peaks and reduces departure delays. This global objective will be achieved by means of Radar sensors to deliver in real time position and strength of the wake vortices and to assess wind conditions including ambient air turbulence by EDR. This paper will present the Radar component of sensors trials campaign, performed at CDG Airport in Spring 2011, providing results of statistical analyses of two UHF wind Profilers Radars and one X-band Wake-Vortex Monitoring Radar data collection, respectively benchmarked with Sodar/Lidar Profiler and 3D Wake-Vortex Monitoring Lidar. The main results were convincing in terms of wake vortex detection. Most of wake vortices were detected in both critical areas. Results show that Radar and Lidar are complementary depending on weather conditions. X-band Radar performances are optimal under rainy conditions when Lidar performances are optimal in dry air. For wind, the overall availability of UHF Wind Profiler Radars data as a function of the height above the surface will be presented (the percentage of the time that reflectivity was sufficient to make a measurement and that the atmosphere was sufficiently homogeneous and stable). The statistical comparison between two UHF profilers (and with Sodar/Lidar Profilers) will be based on histograms of interpolated data availability, wind velocity and direction profiles in specific periods, calculation of bias, standard deviation and correlation for wind velocity and direction by altitude. Using combinations of sensors, models, and real measurements, and thanks to some improved sensors already planned within the project (X-band E-scanning radar), it should be possible to reach operational needs for the Wake-Vortex Advisory system.

Barbaresco, F., Canal, D., Juge, P., Klein, M., Orlandi, F., Ricci, Y. and Schneider, J.-Y.

"RADAR 3D MONITORING OF WAKE-VORTEX HAZARDS, CIRCULATION AND EDR RETRIEVAL/CALIBRATION; SESAR P12.2.2 AND FP7 UFO SENSORS TRIALS AT PARIS-CDG AND TOULOUSE AIRPORTS"

International Radar Conference, Lille, France, 2014.

At airports, runway operation is the limiting factor for the overall throughput; specifically, the fixed and overly conservative ICAO wake turbulence separation minima. The wake turbulence hazardous flows can dissipate quicker because of decay due to air turbulence or be transported out of the way on oncoming traffic by cross-wind, yet wake turbulence separation minima do not consider wind conditions. Indeed, for safety reasons, most airports assume a worst-case scenario and use conservative separations; the interval between aircraft taking off or landing therefore often amounts to several minutes. However, with the aid of accurate wind data and precise measurements of wake vortex by radar sensors, more efficient intervals can be set, particularly when weather conditions are stable. Depending on traffic volume, these adjustments can generate capacity gains, which have major commercial benefits. This paper presents electronic scanning radar trials as Safety Net of a wake turbulence system supporting increased throughput as part of the European ATM research program SESAR, and complementary study UFO (Ultra-Fast wind sensors for wake-vortex hazards mitigation) funded by European FP7 program, on Radar EDR retrieval and Calibration.

Barbaresco, F., Jeantet, A. and Meier, U.

"WAKE VORTEX X-BAND RADAR MONITORING: PARIS-CDG AIRPORT 2008 CAMPAIGN RESULTS AND PROSPECTIVES"

2009 International Radar Conference, October 2009, Bordeaux, France.

In order to improve the capacity of airports in view of the expected increasing amount of traffic the knowledge about the safety issues caused by wake vortices has to be improved. The final goal is to build up a wake vortex alert system to ensure the application of appropriate but not oversized safety distances in all weather conditions. Lidar systems are able to deliver very accurate data, but are also sensitive to the weather conditions like rain and fog. We did trials with the X-band radar BOR-A 550 on Paris-CDG Airport in June 2008 to benchmark Lidar and Radar Technologies. Continuous detection, characterization (strength: circulation) and profiling (age: young/mature/old/decaying) capabilities of wake vortices up to a range of 1500 m have been proved in clear air and rainy weather. The Doppler resolution of around 0.2 m/s used with regularized high Doppler resolution techniques can characterize the wake vortex speed distribution in detail. X-band radar is a full-fledged alternative, which can make a significant contribution to a wake vortex alert system.

Barbaresco, F., Jeantet, A. and Meier, U.

"WAKE VORTEX DATA COLLECTION AND ANALYSIS USING X-BAND RADAR"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-004, September 2007, pp. 1061-1064

In order to improve the capacity of airports in view of the expected increasing amount of traffic the knowledge about the safety issues caused by wake vortices must be improved. The final goal is to build up a wake vortex alert system to ensure the application of appropriate but not oversized safety distances all the time. It is necessary to perform long time data collections of wake vortex encounters on one or more large airports. Lidar systems can deliver very accurate data, but are also sensitive to the weather conditions like rain and fog. THALES did trials with the X-band radar BOR-A 550 on Orly Airport in November, 2006. It was possible to detect wake vortices up to a range of 700 m. The Doppler resolution of around 0.2 m/s used with regularized high Doppler resolution techniques can characterize the wake vortex speed distribution in detail. X-band Radar is a full-fledged alternative, which can make a significant contribution to a wake vortex alert system.

Barbaresco, F., Jeantet, A. and Meier, U.

"WAKE VORTEX DETECTION AND MONITORING BY X-BAND DOPPLER RADAR: PARIS ORLY RADAR CAMPAIGN RESULTS"

The IET International Conference on Radar Systems, Edinburgh, Scotland, October 2007.

Lidar Sensors has been used to collect data on Wake Turbulence and deliver accurate measurements, but their uses is limited to clear air conditions and are not operational in Rain and Fog weathers. On the other hand, Radar is a good complimentary sensor, which can be used for turbulence remote sensing as well. To mature this last solution, THALES did trials on Paris Orly airport in November 2006, and has proved that X-band Doppler Radar was able to detect wake vortexes up to a range of 700 m. Furthermore, the Doppler resolution of around 0.2 m/s used with Regularized High Doppler resolution techniques was able to characterize wake vortex speed distribution in detail. These first trials showed the usability of X-band Radar as an appropriate sensor in different weather conditions like fog, rain, and dry/wet air. Long time data collection trials are planned for different airports to mature this new technology of wake vortex monitoring. The results of the trials that have been performed up to now will be presented. Moreover, the application of methods to match the recorded data with the current knowledge of the fluid mechanics will be shown. As a conclusion, X-band Radar is a full-fledged alternative to a Lidar system, which can make a significant contribution to the improvement of airport capacity and Safety.

Barbaresco, F., Juge, P., Klein, M., Canal, D., Ricci, Y., Schneider, J.-Y., Moneuse, J.-F., Lavergne, E. and Mutuel, L.

"BOOM OF AIRPORT CAPACITY BASED ON WAKE-VORTEX HAZARDS MITIGATION SENSORS AND SYSTEMS"

Airports in Urban Networks, 2014, Paris, France.

At airports, surface operation on the runway is the limiting factor for the overall throughput; specifically, the fixed and overly conservative ICAO wake turbulence separation minima. The wake turbulence hazardous flows can dissipate quicker because of decay due to air turbulence or be

transported out of the way on oncoming traffic by cross-wind, yet wake turbulence separation minima do not consider wind conditions. Indeed, for safety reasons, most airports assume a worst-case scenario and use conservative separations; the interval between aircraft taking off or landing therefore often amounts to several minutes. However, with the aid of accurate wind data and precise measurements of wake vortex by radar sensors, more efficient intervals can be set, particularly when weather conditions are stable. Depending on traffic volume, these adjustments can generate capacity gains, which have major commercial benefits. This paper presents the developments of a wake turbulence system supporting increased throughput as part of the European ATM research program SESAR, and complementary technology study UFO (Ultra-Fast wind sensors for wake-vortex hazards mitigation) funded by European FP7 program.

Barbaresco, F., Juge, P., Klein, M., Canal, D., Ricci, Y., Schneider, J.-Y., Moneuse, J.-F., Lavergne, E. and Mutuel, L.

"WAKE VORTEX DETECTION, PREDICTION AND DECISION SUPPORT TOOLS IN SESAR PROGRAM"

32nd Digital Avionics Systems Conference, Paper 6B1, October 2013, East Syracuse, NY.

This paper presents the developments of a wake turbulence system supporting increased throughput as part of the European ATM research program SESAR. This wake turbulence system is designed to, punctually or permanently, reduce landing and departure wake turbulence separations, thus increasing the runway throughput in such a way that arrival demand peaks and departure delays are safety absorbed. This global objective is by deploying radar sensors to deliver real-time position and strength information of the wake vortices and to assess wind conditions including ambient air turbulence via Eddy Dissipation Rate. To further address the optimization of throughput, two extensions for the use of wake turbulence system are considered for the terminal area and the runway rollout. These extensions connect the ground system with the aircraft to maximize benefits. The first application is the optimization of aircraft sequence via point-merge procedure, which is part of interval management operational improvement. The second application relates to the optimization of runway exit based on assessment of runway condition and aircraft-based braking capability to select the best runway exit for both the aircraft objectives and the runway throughput.

Barbaresco, F., Juge, P., Klein, M., Ricci, Y., Schneider, J.-Y. and Moneuse, J.-F.

"OPTIMISING RUNWAY THROUGHPUT THROUGH WAKE VORTEX DETECTION, PREDICTION AND DECISION SUPPORT TOOLS"

ESAV'11 Workshop, September 2011, Capri, Italy.

Currently at many airports, runway is the limiting factor for the overall throughput. Among the most important parameters are the fixed wake turbulence separation minima expressed in time for take-off clearance and by distance for arrivals on final approach. This wake turbulence separation limits the arrival and departure flow on many airports in Europe already today. Existing departure and arrival wake turbulence separations are sometimes considered over conservative as they do not take into

account meteorological conditions likely to shift, reduce or alleviate their circulations. This paper will present the main aspects of a SESAR project that defines, analyses and develops a verified wake turbulence system according to related operational concept improvements in order to, punctually or permanently, reduce landing and departure wake turbulence separations and, therefore, to increase the runway throughput in such a way that it safely absorbs arrival demand peaks and/or reduces departure delays. This global objective will be achieved by means of developing a wake vortex decision support system able to deliver in real time position and strength of the wake vortices and to predict their behavior and potential impact on safety and capacity, taking in account actual weather information as well as the airport specific climatological conditions, aircraft characteristics (generated wake vortex and wake vortex sensitivity) and airport runways layout. These functionalities will be progressively included in the wake vortex decision support system to be validated and deployed on airports in order to optimize the runway throughput and reduce delays.

Barbaresco, F., Juge, P., Klein, M., Ricci, Y., Schneider, J.-Y. and Moneuse, J.-F.

"OPTIMISING RUNWAY THROUGHPUT THROUGH WAKE VORTEX DETECTION, PREDICTION AND DECISION SUPPORT TOOLS"

Journal of Air Traffic Control, Vol. 54, No. 3, Summer 2012, pp. 21-37.

Aircraft creates wake vortices in different flying phases. To avoid jeopardizing flight safety by wake vortices encounters, time/distance separations have been conservatively increased, thus restricting runway capacity. The concern is higher during taking off and landing phases, as aircraft are less easy to maneuver. These vortices usually dissipate quickly (decay due to air turbulence or transport by cross-wind), but most airports operate for the safest scenario, which means the interval between aircraft taking off or landing often amounts to several minutes. However, with the aid of accurate wind data and precise measurements of wake vortex, more efficient intervals can be set, particularly when weather conditions are stable. Depending on traffic volume, these adjustments can generate capacity gains, which have major commercial benefits. Wake vortices are a natural byproduct of lift generated by aircraft and can be considered as two horizontal tornados trailing behind the aircraft. A trailing aircraft exposed to the wake vortex turbulence of a lead aircraft can experience an induced roll moment (bank angle) that is not easily corrected by the pilot or the autopilot. However, these distances can be safely reduced with the aid of smart planning techniques of future Wake Vortex Decision Support Systems based on Wake Vortex detection/monitoring and Wake Vortex Prediction (mainly transport estimation by cross-wind), significantly increasing airport capacity. This limiting factor will be significantly accentuated soon with the arrival of new heavy aircraft: Airbus A380, a stretched version of Boeing B747-8. Radar and Lidar sensors are low-cost technologies with highly performing complementary wake vortex detection capability in all weather conditions compared to others sensors that suffer of limited one. Radar and Lidar are promising sensors for turbulence remote sensing on airport, for all kinds of aviation weather hazards (wake vortex, windshear, micro-bursts, atmospheric turbulences) with ability to work operationally in a collaborative way, in different severe weather conditions like fog, rain, wind, and dry air.

Barbaresco, F., Thobois, L., Dolfi-Bouteyre, A., Jeannin, N., Wilson, R., Valla, M., Hallermeyer, A., Feneyrou, P., Brion, V., Besson, L., Cariou, J. P., Leviandier, L., Pillet, G. and Dolfi, D.

"MONITORING WIND, TURBULENCE AND AIRCRAFT WAKE VORTICES BY HIGH RESOLUTION RADAR AND LIDAR REMOTE SENSORS IN ALL WEATHER CONDITIONS"

Probe Material by Electromagnetic Waves, Union Radio-Scientifique Internationale, Paris, France, March 2015, pp. 81-110.

Air flows in the troposphere have a major impact on air traffic safety and operations. By air flows, several phenomena can be distinguished with different spatial and temporal characteristic scales: the mean wind itself, its rapid fluctuations, called turbulence, and wake vortices which are structured motions generated by each aircraft. At low altitudes, during take-off or landing phases, distance separations between aircrafts that limit today airport capacities were set up forty years ago to prevent the risk of wake vortices encounters in worst conditions. These out-of-date distance separations must be optimized since strength and lifetime of wake vortices vary a lot with weather conditions, like winds and turbulence. At high altitudes, during enroute flight phase, wake vortices as well as clear air turbulence can have a dramatic impact on aircraft safety. In this study, the way to measure wind, turbulence and wake vortices with new remote sensing techniques, 1.5 micron Coherent Doppler LIDAR, X-Band RADAR, and UV direct detection LIDAR, is detailed for ground-based or airborne applications. Sensor simulation tools and post-processing algorithms have been developed to retrieve wind, turbulence, especially EDR (eddy dissipation rate) and wake vortices parameters from sensors data and to assess their accuracy.

Barbaresco, F., Wasselin, J. P., Jeantet, A. and Meier, U.

"WAKE VORTEX MONITORING & PROFILING BY DOPPLER X-BAND RADAR IN ALL WEATHER CONDITIONS"

6th EUROCONTROL Innovative Research Workshop & Exhibition, December 2007, Bretigny sur Orge, France, pp. 225-236.

To improve the capacity of airports in view of the expected increasing amount of traffic the knowledge about the safety issues caused by wake vortices must be improved. The final goal is to build up a wake vortex alert system to ensure the application of appropriate but not over-sized safety distances in all weather conditions. Lidar systems can deliver very accurate data, but are also sensitive to rain and fog. THALES did trials with the X-band radar BOR-A 550 on Orly Airport in November 2006 at Initial Take-Off and in September 2007 at ILS Interception Area. Operational continuous Detection, characterization (strength: circulation) and profiling (age: young/mature/old/decaying) capabilities of wake vortices up to a range of 1500 m have been proved in clear air and rainy weather. Opportunity detection of wake vortex was also obtained at long range until 7 Km in clear air. The Doppler resolution of around 0.2 m/s used with regularized high Doppler resolution techniques can characterize the wake vortex speed distribution in detail. X-band Radar is a full-fledged alternative, which can make a significant contribution to a wake vortex alert system.

Barbaresco, F., Wasselin, J. P., Jeantet, A. and Meier, U.

"STUDY OF WAKE VORTEX ROLL UP SPIRAL GEOMETRY BASED ON REAL CONDITIONS AIRPORT DOPPLER RADAR TRIALS (NEAR THE GROUND ALONG RUNWAY AND IN GLIDE SLOPE)"

Int'l. Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

High Doppler resolution of X-band Radar can characterize wake vortex spiral geometry. Wake vortex Doppler radar signature can estimate: tangential speed in wake roll-up, wake vortex strength by circulation estimations, wake vortex age, and wake vortex spiral geometry. These radar trials have been made in real conditions at Paris Orly Airport in two phases: horizontal scanning of runways and vertical scanning of ILS interception area (entrance of glide slope), in wet and dry conditions. Additional trials are scheduled in 2008 at Paris CDG Airport.

Barbaresco, F., Wasselin, J. P., Jeantet, A. and Meier, U.

"WAKE VORTEX PROFILING BY DOPPLER X-BAND RADAR: ORLY TRIALS AT INITIAL TAKE-OFF AND ILS INTERCEPTION CRITICAL AREAS"

2008 International Radar Conference, IEEE, May 2008, Rome, Italy.

To improve the capacity of airports in view of the expected increasing amount of traffic the knowledge about the safety issues caused by wake vortices must be improved. The final goal is to build up a wake vortex alert system to ensure the application of appropriate but not oversized safety distances in all weather conditions. Lidar systems can deliver very accurate data, but are also sensitive to the weather conditions like rain and fog. We did trials with the X-band radar BOR-A 550 on Orly Airport in November 2006 at initial take-off and in October 2007 at ILS interception area. Continuous detection, characterization (strength: circulation) and profiling (age: young/mature/old/decaying) capabilities of wake vortices up to a range of 700 m have been proved in clear air and rainy weather. Opportunity detection of wake vortex was also obtained at long range until 7 Km in clear air. The Doppler resolution of around 0.2 m/s used with regularized high Doppler resolution techniques can characterize the wake vortex speed distribution in detail. X-band radar is a full-fledged alternative, which can make a significant contribution to a wake vortex alert system.

Barbeau, Z. P. and Jacob, J. D.

"FLIGHT TEST OF SMALL UAS WAKE VORTEX ENCOUNTERS -- PART 1: CONTROL SYSTEM DEVELOPMENT AND EVALUATION"

AIAA Paper 2017-0957, January 2017, Grapevine, TX.

An exponential growth in the number of unmanned aircraft systems (UAS) operating within U.S. national airspace is projected through the next two decades. Regulations for small UAS weighing under 55 pounds have been enacted per Federal Aviation Regulations (FAR) part 107. Without specific authorization through a certificate of operation or section 333 exemption, small UAS will initially be restricted from integrating with controlled air traffic due to see and avoid criteria. As UAS are

developed with robust see and avoid capability, integration into the national airspace is inevitable. Wake vortex encounters of similarly sized small UAS could prove problematic in a future, integrated national airspace scenario. Historical data has shown that wake vortex encounters most frequently occur during the takeoff, approach, and landing phases of flight. Flight testing of small UAS is planned to characterize and provide recommendations regarding wake vortex encounters of fixed wing and rotary aircraft during each phase of flight. Part one of this paper offers discussion of flight test methodology and specific operational procedures that were developed as part of the test campaign.

Barber, M. R. and Tymczyszyn, J. J.

"WAKE VORTEX ATTENUATION FLIGHT TESTS: A STATUS REPORT"

The 1980 Aircraft Safety and Operating Problems Conf., Part 2, March 1981, NASA Langley Research Center, pp. 387-408

Flight tests were conducted to evaluate the magnitude of aerodynamic attenuation of the wake vortices of large transport aircraft that can be achieved using static spoiler deflection and lateral control oscillation. These methods of attenuation were tested on Boeing B-747 and Lockheed L-1011 commercial transport aircraft. Evaluations were made using probe aircraft, photographic and visual observations, and ground-based measurements of the vortex velocity profiles. The magnitude of attenuation resulting from static spoiler deflection was evaluated both in and out of ground effect. A remotely piloted QF-86 drone aircraft was used to probe the attenuated vortices in flight in and out of ground effect, and to make landings behind an attenuated B-747 airplane at reduced separation distances.

Barber, M. R., Hastings, Jr., E. C., Champine, R. A. and Tymczyszyn, J. J.

"VORTEX ATTENUATION FLIGHT EXPERIMENTS"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 369-403

Flight tests evaluating the effects of altered span loading, turbulence ingestion, combinations of mass and turbulence ingestion, and combinations of altered span loading turbulence ingestion on trailed wake vortex attenuation were conducted. Span loadings were altered in flight by varying the deflections of the inboard and outboard flaps on a B-747 aircraft. Turbulence ingestion was achieved in flight by mounting splines on a C-54G aircraft. Mass and turbulence ingestion was achieved in flight by varying the thrust on the B-747 aircraft. Combinations of altered span loading and turbulence ingestion were achieved in flight by installing a spoiler on a B-747 aircraft. The characteristics of the attenuated and unattenuated vortices were determined by probing them with smaller aircraft. Acceptable separation distances for encounters with the attenuated and unattenuated vortices are presented.

Barber, M. R., Kurkowski, R. L., Garodz, L. J., Robinson, G. H., Smith, H. J., Jacobsen, R. A., Stinnett, Jr., G. W., McMurtry, T. C., Tymczyszyn, J. J., Devereaux, R. L. and Bolster, A. J.

"FLIGHT TEST INVESTIGATION OF THE VORTEX WAKE CHARACTERISTICS BEHIND A BOEING 727 DURING TWO-SEGMENT AND NORMAL ILS APPROACHES"

FAA-NA-75-151, January 1975, NASA Dryden Flight Research Center, Edwards, CA

A series of flight tests were performed to evaluate the vortex wake characteristics of a Boeing 727 (B727-200) aircraft during conventional and two-segment ILS approaches. Twelve flights of the B727, equipped with smoke generators for vortex marking, were flown wherein its vortex wake was intentionally encountered by a Lear Jet model 23 (LR-23) or a Piper Twin Comanche (PA-30); and its vortex location during landing approach was measured using a system of photo-theodolites. The tests showed that at a given separation distance there were no readily apparent differences in the upsets resulting from deliberate vortex encounters during the two types of approaches. Timed mappings of the position of the landing configuration vortices showed that they tended to descend approximately 91 meters (300 feet) below the flight path of the B727. The flaps of the B727 have a dominant effect on the character of the trailed wake vortex. The clean wing produces a strong, concentrated vortex. As the flaps are lowered the vortex system becomes more diffuse. Pilot opinion and roll acceleration data indicate that 4.5 nautical miles would be a minimum separation distance at which roll control could be maintained during parallel encounters of the B727's landing configuration wake by small aircraft. This minimum separation distance is generally in scale with results determined from previous tests of other aircraft using the same roll control criteria.

Barber, T. and Kurts, P.

"DOWNSTREAM EVOLUTION OF WINGTIP VORTICES PRODUCED FROM AN INVERTED WING"

The Aeronautical Journal, Vol. 119, No. 1216, June 2015, pp. 747-763.

Counter-rotating vortices form from the opposite edges of lifting surfaces, and gradually move laterally and dissipate as they travel downstream (as seen in a wing-fixed reference frame). Under ground-effect conditions, the vortex from a lifting wing -- such as that used in an aircraft application -- moves laterally outboard from the wingtip as it progresses downstream; for a downforce wing in ground effect -- such as that used in an automotive application -- the vortex moves laterally inboard. An interesting case is the situation where the inboard moving vortices become near each other. The objective of the present study was to investigate counter-rotating vortices produced from a low aspect ratio downforce wing operating in ground effect. The pair of vortices move towards each other and mutually induce an upwards directed motion which in turn reduces the inboard movement driven by the ground effect. Experimental data gained from three-dimensional Laser Doppler Anemometry in a moving ground wind-tunnel was used to validate a Large Eddy Simulation computational result.

Barbre Jr, R. E.

"QUALITY CONTROL ALGORITHMS FOR THE KENNEDY SPACE CENTER 50-MHZ DOPPLER RADAR WIND PROFILER WINDS DATABASE"

Journal of Atmospheric and Oceanic Technology, Vol. 29, December 2012, pp. 1731-1743.

This paper presents the process used by the Marshall Space Flight Center Natural Environments Branch (EV44) to quality control (QC) data from the Kennedy Space Center's 50-MHz Doppler radar wind profiler (DRWP) for use in vehicle wind loads and steering commands. The database has been built to mitigate limitations of using the currently archived databases from weather balloons. The DRWP database contains wind measurements from approximately 2.7- to 18.6-km altitude at roughly 5-min intervals for the August 1997-December 2009 period of record, and the extensive QC process was designed to remove spurious data from various forms of atmospheric and non-atmospheric artifacts. The QC process is largely based on DRWP literature, but two new algorithms have been developed to remove data contaminated by convection and excessive first-guess propagations from the median filter/first guess algorithm. In addition to describing the automated and manual QC process in detail, this paper describes the extent of the data retained. Roughly 58 percent of all possible wind observations exist in the database with approximately 100 times as many complete profile sets existing relative to the EV44 balloon databases. This increased sample of near-continuous wind profile measurements may help to increase launch availability by reducing the uncertainty of wind changes during launch countdown.

Barkel, B.

"SIMULATION OF A HELICOPTER/LIGHT AIRCRAFT WAKE ENCOUNTER"

MS Thesis, September 2011, Univ. of Liverpool, Liverpool, England.

This project is investigating the effect of light helicopter wakes using computer-based simulation methods. A literature survey was conducted to study current vortex models and numerical techniques for vortex modeling and wake encounter simulation. Simple numerical models for vortex trajectory and induced velocities were written for both fixed-wing aircraft and rotorcraft. The fixed-wing program uses the method of images to simulate the ground and an iterative Biot-Savart computation scheme to develop the vortex trajectories. The rotorcraft wake is based on the Beddoes prescribed wake model, and calculates the trajectories of the vortices based on mathematical equations derived from experimental data. Each model can be used to generate both time-varying and static wakes, where the induced velocities are calculated on a grid using the Biot-Savart law with Scully vortex cores superimposed over the vortex filaments. These wakes are then inserted into FLIGHTLAB for real-time flight simulation. Preliminary tests found that the magnitude of the response from the following aircraft largely depends on the length of time it spends within the wake; encounters where the aircraft is traveling slower and enter the wake from directly behind pose more danger than those where the aircraft is traveling faster and encounter the wake at an angle. Crosswinds play a relatively minor role, as they can affect the trajectory of the wake but, due to the simplicity of the current models, they do not affect the structure of the core or alter the induced velocities by a significant amount relative to the aircraft's speed. A methodology for modifying the FLIGHTLAB fixed-wing model architecture to accept time-varying wakes was developed.

Barker, B. C., Burnham, D. C. and Rudis, R. P.

"WAKE SENSOR EVALUATION PROGRAM AND RESULTS OF JFK-1 WAKE VORTEX SENSOR INTERCOMPARISONS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 324-332

In November 1996, several sensing technologies (in situ anemometers, cw lidar, fan-beam sodar, RASS, and scintillometer) was deployed at JFK airport to evaluate their potential for meeting the wake sensing requirements of the AVOSS system. Of particular interest were sensors that can detect meteorological conditions as well as detect wake vortices. The tests were conducted near the middle marker of Runway 31R, where landing aircraft are about 50 m above the ground. Based on the test results, an additional test was scheduled for May 1997.

Barker, B. C., Koch, G. J. and Nguyen, D. C.

"AN OPERATIONAL WAKE VORTEX SENSOR USING PULSED COHERENT LIDAR"

Proceedings of 19th International Laser Radar Conf., Part 2, July 1998, pp. 681-684

NASA and FAA initiated a program in 1994 to develop methods of setting spacings for landing aircraft by incorporating information on the real-time behavior of aircraft wake vortices. The goals of this effort are to ensure that separation standards are adequate for safety and to reduce aircraft spacing for higher airport capacity. Preliminary studies indicate that the airline industry would save considerable money and incur fewer passenger delays if a dynamic spacing system could reduce separations at major hubs during inclement weather to the levels routinely achieved under visual flight conditions. The sensor described herein may become part of the dynamic spacing system known as the 'Aircraft VORtex Spacing System' (AVOSS) that will interface with a future air traffic control system. The wake vortex sensor will periodically provide data to validate AVOSS predictions. The first measurements of wake vortices using a pulsed lidar were made by Coherent Technologies, Inc. using a 2-micron solid-state, flashlamp-pumped system operating at 5 Hz. This system was first deployed at Denver's Stapleton Airport. Pulsed lidar has been selected as the baseline technology for an operational sensor due to its longer-range capability.

Barker, Jr., B. C., Brockman, P. and Koch, G. J.

"LASER RADAR WATCHES THE FRIENDLY SKIES"

Photonics Spectra, Vol. 31, No. 4, April 1997, pp. 94-98

Lasers are probing aircraft wake vortex effects to improve commercial airline safety and traffic. Laser radar is studying wake vortices to help determine whether planes at busy airports can safely fly closer together during bad weather -- thus reducing delays.

Barker, S. J. and Crow, S. C.

"THE MOTION OF TWO-DIMENSIONAL VORTEX PAIRS IN GROUND EFFECT"

PR-4, May 1976, Poseidon Research, Sherman Oaks, CA

A new technique for generating a pair of line vortices in the laboratory has been developed. The mean flow of these vortices is highly two-dimensional, although most of the flow field is turbulent. This two-dimensionality permits the study of vortex motions in the absence of the Crow mutual induction instability and other three-dimensional effects. The vortices are generated in a water tank of dimensions 15 x 122 x 244 cm. They propagate vertically and their axes span the 15 cm. width of the tank. One wall of the tank is transparent, and the flow is visualized using fluorescein dye. High speed photography is used to study both the transition to turbulence during the vortex formation process and the interaction of the turbulent vortices with a simulated ground plane. The interaction of the vortex pair with the ground plane does not follow the predictions of potential flow theory for line vortices. Although total circulation is apparently conserved, the vortices remain at a larger distance from the ground than expected and they eventually 'rebound' or move away from the ground. Differences between a free surface boundary condition and a smooth or rough ground plane are discussed. The ground plane interaction is qualitatively very similar to that of aircraft trailing vortices observed in recent flight tests.

Barker, S. J. and Crow, S. C.

"THE MOTION OF TWO-DIMENSIONAL VORTEX PAIRS IN A GROUND EFFECT"

J. Fluid Mech., Vol. 82, Part 4, 1977, pp. 659-671

A new technique for generating a pair of line vortices in the laboratory has been developed. The mean flow of these vortices is highly two-dimensional, although most of the flow field is turbulent. This two-dimensionality permits the study of vortex motions in the absence of the Crow mutual induction instability and other three-dimensional effects. The vortices are generated in a water tank of dimensions 15 x 122 x 244 cm. They propagate vertically and their axes span the 15 cm width of the tank. One wall of the tank is transparent, and the flow is visualized using fluorescein dye. High speed photography is used to study both the transition to turbulence during the vortex formation process and the interaction of the turbulent vortices with a simulated ground plane. Transition occurs first in an annular region surrounding the core of each vortex, starting with a shear-layer instability on the rolled-up vortex sheet. The turbulent region then grows both radially inwards and radially outwards until the entire recirculation cell is turbulent. A 'relaminarization' of the vortex core appears to take place somewhat later. The interaction of the vortex pair with the ground plane does not follow the predictions of potential-flow theory for line vortices. Although the total circulation is apparently conserved, the vortices remain at a larger distance from the ground than is expected and eventually 'rebound' or move away from the ground. Differences between a free-surface boundary condition and a smooth or rough ground plane are discussed. The ground-plane interaction is qualitatively very similar to that of aircraft trailing vortices observed in recent flight tests.

Barker, S. J. and Crow, S. C.

"CORE INSTABILITIES OF A VORTEX PAIR"

Bull. Am. Physical Society, Vol. 20, No. 11, November 1975, p. 1428

Aircraft wake vortices have stimulated great interest in the means by which vortex pairs decay. The mechanism of vortex decay outside ground effect can be divided into two classes: mutual induction instability and vortex core instability. The present study looks at the second class both experimentally and analytically. By the Rayleigh criterion, isolated vortices are stable to small axisymmetric disturbances. However, it is shown that a wrapped-up vortex sheet is unstable to helical disturbances having azimuthal wavenumbers greater than three. Any tangential velocity distribution with an inflection point in the rotational region is unstable to such disturbances. The experiment used to visualize the instabilities is a two-dimensional analog of the vortex wake, in which distance behind the aircraft is represented by time from the creation of the vortex pair. The experiment takes place in a water tank of dimensions 0.5 by 4 by 8 feet. The vortices are oriented across the 0.5 feet width of the tank, visualized by dye injection, and photographed by a high-speed movie camera.

Barla, C., Favier, D., Rondot, C., Maresca, C., Raffel, M., Richard, H., Bosbach, J. and Henning, H.

"PIV MEASUREMENTS OF THE VORTICAL WAKE BEHIND TILT-ROTOR BLADES"

13th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Paper No. 1072, Lisbon, Portugal, June 2006

This paper concerns a collaborative research work between DLR of Gottingen and LABM of Marseille which aims to create a new experimental data base characterizing the tilt-rotor wake and the associated vortex structures. This study will provide detailed flow data on the aerodynamic interactions causes which occur on a tilt-rotor aircraft including a rotor, a nacelle, a fixed wing and an end plate simulating the fuselage. Experiments have been performed in the LABM S1L wind-tunnel at 3 different flight configurations which correspond to hover, conversion and cruise flights. The stereoscopic PIV system generates an illuminating laser sheet in a Z-plane normal to the uniform free stream velocity. PIV measurements have been performed at different Z-planes distributed at different distance downstream the rotor (in the wake region between the rotor and the wing and above the fixed wing) in both the conversion and cruise flight configurations and for different parametric conditions of the rotor shaft angle, the blade rotational frequency, the upstream velocity, the advancing parameter, and the collective pitch angle value. For these different parametric conditions, the tip vortex path and the associated 3C velocity field shed from the blade have been determined in the early stages of the tip vortex shedding corresponding to 3 azimuth positions and in a fixed downstream plane located at $Z/R=0$. The XY-plots of the velocity vector clearly show the flow perturbation generated by the blade passage and the vortex development and propagation from the tip of the emitting blade. Moreover, from such PIV measurements performed at different downstream distances from the rotor and at different blade azimuth positions the tip vortex paths have been reconstructed both in the wake region between the rotor and the wing and above the wing surface. The wake data provide a better understanding on both the vortex dynamics and the behavior of vortical structures interacting with the wing on a tilt-rotor configuration.

Barnes, C. J., Visbal, M. R. and Gordnier, R. E.

"INVESTIGATION OF AEROELASTIC EFFECTS IN STREAMWISE-ORIENTED VORTEX/WING INTERACTIONS"

AIAA Paper 2014-1281, January 2014, National Harbor, MD.

This work explores the interaction of streamwise vortices generated by a leader wing on rigid and flexible follower wings in a close homogeneous V-formation. Computations are performed using high-fidelity implicit LES simulations coupled with a geometrically nonlinear Reissner-Mindlin finite element plate model. Several areas are explored in order to provide a better understanding of the unsteady flow structure, aerodynamic loading, and aeroelastic response that might be encountered by light-weight high aspect ratio wings in close-formation. First, exploration of positioning between rigid wings shows interaction between the incident streamwise vortex and follower wing tip vortex. These effects include vortex-dipoles, instability of the vortex cores, and bifurcation which can all significantly reorient wake features with a small change in lateral or vertical positioning. Each case demonstrates an enhanced lift-to-drag ratio while unsteady loading remains comparable to that of a single wing. This suggests fluctuations in the incident vortex due to atmospheric disturbances or unintended/uncontrollable aircraft motion might be a more dominant source of buffeting behavior in the case of flexible wings. Such an effect would be magnified in the presence of a stronger incoming vortex as shown in the case of increasing the leader-wing angle of attack. Second, computation of flexible wings in close-formation primarily results in static-aeroelastic spanwise deflection of the wing and repositioning of the vortex-encounter. Consequently, large changes in flow structure and loading result from small static spanwise bending deformations. A small dynamic response is observed in the twisting-mode of the moderately flexible case which amplifies pitching-moment fluctuations and would have implications on the fatigue life of the wing structure. Interestingly, this source of unsteadiness was diminished on the vortex-encounter side of the wing.

Barnes, C. J., Visbal, M. R. and Huang, G. P.

"EFFECT OF BENDING OSCILLATIONS ON A STREAMWISE-ORIENTED VORTEX INTERACTION"

AIAA Paper 2015-3303, June 2015, Dallas, TX.

This work explores the feedback response and unsteady flow structure due to forced bending oscillations on a q -vortex impinging on a flat plate wing inboard of the wingtip and aligned with the leading-edge. The effects of bending amplitude are explored for A/c greater than or equal to 0.025 and less than or equal to 0.1 at a bending frequency of $f_{sub b} = f_c/(U_{sub infinity}) = 0.5$. The low-frequency motion requires a large amplitude to provide significant impact to the general flow structure. Low-frequency, large-amplitude motion provides several important effects. Upstream of the leading-edge, bending oscillations alleviate the upstream influence experienced in the static rigid wing case consequently diminishing helical instability in the impinging vortex. This observation suggests a favorable application of wing dynamics in vortex-surface interactions. Very close to the leading-edge the vortex is forced between adverse and favorable pressure gradients which alternately promote growth and removal of helical instability, respectively. Above the wing, the initially coherent vortex is

shown to decompose into a series of spanwise substructures when it passes over and then pinches off from the suction-side. The effects of bending frequency are evaluated for f_{sb} greater than or equal to 0.5 and less than or equal to 2 at an amplitude of $A/c = 0.025$. Bending oscillations of $f_{sb} = 1$, close to the instability frequency $S t_c = 0.9$, could impose a slight shift in vortex behavior causing the instability to lock into the bending frequency. High-frequency, low-amplitude motion inhibits coherent propagation of the incident vortex over either side of the wing, but fails to induce higher-modal instability upstream of the leading edge.

Barnes, J. R.

"SIDE FORCE ON A WING BODY COMBINATION DUE TO TRAILING VORTICES"

ARC Report CP-669, July 1962, Royal Aircraft Establishment, Farnborough, England. (Also, RAE Tech. Note Aero. 2834.)

A long cylindrical body has two wings attached symmetrically but set at equal and opposite angles relative to its axis. When this system is placed at incidence in a uniform flow a side force is experienced. The purpose of this note is to make some estimate of the magnitude of this side force. The vortices shed by the wings are assumed to have rolled up at the trailing edge and their paths are calculated using slender body theory. Expressions are given for the forces experienced by the body aft of the wings, and some numerical calculations made.

Baron, A., Boffadossi, M. and Deponte, S.

"NUMERICAL SIMULATION OF VORTEX FLOWS PAST IMPULSIVELY STARTED WINGS"

AGARD Vortex Flow Dynamics, Politecnico di Milano, Milan, Italy, July 1991

A nonlinear unsteady vortex lattice method is used to predict the geometry of the wakes and the distribution of the aerodynamic loads on impulsively started wings. The wings are assumed to have negligible thickness, arbitrary aspect ratio, and planform. They can undergo a general unsteady motion. Multi-wing configurations can be treated. Wakes can be released in the flow field from any of the sharp edges of the lifting surfaces, depending on planform, aspect ratio, and attitude of the wings. Particular emphasis is placed on the simulation of vortex core diffusion which is regarded as a prominent factor in a correct development of unsteady wakes. A vortex core diffusion model is proposed which seems to be able to deal even with the severe roll-up of the shear layers past highly swept multi-wing configurations with leading edge separation. The prediction capabilities of the method are verified by comparison of the numerical results with experimental data published by various authors.

Baronti, P. and Elzweig, S.

"FOG FORMATION AND DISPERSAL BY TRAILING VORTICES"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 561-573.

A model is presented to explain why fogs can be maintained for extended periods of time. The model considers fog as a dynamical system whereby droplets depletion through fall is balanced by a continuous process of evaporation and condensation. The controlling parameters of the process are indicated. Possible means of fog dispersal by the velocity field induced by trailing vortices are suggested.

Barre, S., Bogey, C. and Bailly, C.

"DNS OF A HIGH-ASPECT-RATIO ELLIPTIC VORTEX AND ITS GENERATED NOISE"

AIAA Paper No. 2005-2956, Monterey, CA, May 2005

The aerodynamic evolution and the acoustic radiation of elliptic vortices with various aspect ratios are investigated by solving numerically the full compressible Navier-Stokes equations. Three behaviors are observed according to the aspect ratio a/b where a and b are the major and minor semi-axes of the vortices. At the small aspect ratio (1.2) the vortex rotates at a constant angular velocity and radiates like a rotating quadrupole. The acoustic radiation is in very good agreement with a reference analytical solution. At the moderate aspect ratio (5.0), the vortex is initially unstable. However, its aspect ratio decreases due to an axisymmetrization process, which inhibits the growth of instabilities. The noise level then decreases and the radiation frequency increases. The far-field is found to be in good agreement with the reference solution, which has been modified to take into account the evolution of the shape of the vortex. For vortices with larger aspect ratios (6 or more), axisymmetrization does not occur quickly enough to stop the growth of instabilities, which splits the vortices. Then various mergings are found to occur. For instance, in the case of aspect ratio 6, several successive switches between an elliptic state and a configuration of two co-rotating vortices are observed. The sound field remains weakly affected by the switches. The present results show that the initial value of the aspect ratio yields the relative weight of the axisymmetrization which stabilizes the vortex, and of the growth of instabilities which tends to split it.

Barre, S., Bogey, C. and Bailly, C.

"DIRECT SIMULATION OF ISOLATED ELLIPTIC VORTICES AND OF THEIR RADIATED NOISE"

Theoretical Computational Fluid Dynamics, Vol. 22, 2008, pp. 65-82.

The aerodynamic evolution and the acoustic radiation of elliptic vortices with various aspect ratios and moderate Mach numbers are investigated by solving numerically the full compressible Navier-Stokes equations. Three behaviors are observed according to the aspect ratio a/b where a and b are the major and minor semi-axes of the vortices. At the small aspect ratio (1.2) the vortex rotates at a constant angular velocity and radiates like a rotating quadrupole. At the moderate aspect ratio (5.0), the vortex is initially unstable. However, the growth of instability waves is inhibited by the return to axisymmetry which decreases its aspect ratio. The noise level becomes lower with time and the radiation frequency increases. For vortices with larger aspect ratios (6 or more), the return to

axisymmetry does not occur quickly enough to stop the growth of instabilities, which splits the vortices. Various mergers are then found to occur. For instance, in the case of aspect ratio 6, several successive switches between an elliptic state and a configuration of two co-rotating vortices are observed. The present results show that the initial value of the aspect ratio yields the relative weight between the return to axisymmetry which stabilizes the vortex and the growth of instabilities which tends to split it.

Barrer, J. N.

"CONCEPT FOR USING MULTIPLE GLIDE SLOPE ANGLES FOR WAKE VORTEX AVOIDANCE ON PARALLEL IFR APPROACHES"

FAA-DL5-86-3, November 1986, Mitre Corp., McLean, VA

For parallel runways separated by less than 2500 feet, the longitudinal separation between aircraft on adjacent approaches must be maintained at the same distance as if the aircraft were on a single runway. The hazard associated with trailing wing tip vortices is the major hindrance to reducing separation distances during instrument approaches. This report shows how separations can be safely reduced on closely spaced parallel runways. The analysis exploits the use of staggered runway thresholds, multiple glide slope angles, and wind measurement devices to ensure vortex avoidance. The analysis is applied to Denver Stapleton International Airport.

Barrett, S. R. H., Britter, R. E. and Waitz, I. A.

"IMPACT OF AIRCRAFT PLUME DYNAMICS ON AIRPORT LOCAL AIR QUALITY"

Atmospheric Environment, Vol. 74, 2013, pp. 247-258.

Air quality degradation in the locality of airports poses a public health hazard. The ability to quantitatively predict the air quality impacts of airport operations is of importance for assessing the air quality and public health impacts of airports today, of future developments, and for evaluating approaches for mitigating these impacts. However, studies such as the Project for the Sustainable Development of Heathrow have highlighted shortcomings in understanding of aircraft plume dispersion. Further, if national or international aviation environmental policies are to be assessed, a computationally efficient method of modeling aircraft plume dispersion is needed. To address these needs, we describe the formulation and validation of a three-dimensional integral plume model appropriate for modeling aircraft exhaust plumes at airports. We also develop a simplified concentration correction factor approach to efficiently account for dispersion processes particular to aircraft plumes. The model is used to explain monitoring station results in the London Heathrow area showing that pollutant concentrations are approximately constant over wind speeds of 3-12 m/s, and is applied to reproduce empirically derived relationships between engine types and peak NO_x concentrations at Heathrow. We calculated that not accounting for aircraft plume dynamics would result in a factor of 1.36-2.3 over-prediction of the mean NO_x concentration (depending on location), consistent with empirical evidence of a factor of 1.7 over-prediction. Concentration correction factors

are also calculated for aircraft takeoff, landing, and taxi emissions, providing an efficient way to account for aircraft plume effects in atmospheric dispersion models.

Barricau, P., Lempereur, C., Mignosi, A., Mathe, J.-M., Roehle, I., Schodl, R. and Willert, C.

"ONERA/DLR ACTIVITIES ON DOPPLER GLOBAL VELOCIMETRY AND ITS QUALIFICATION FOR WIND TUNNEL APPLICATIONS"

3rd ONERA-DLR Aerospace Symposium, June 2001, Paris, pp. S4-4/1-10.

Two Doppler Global Velocimetry Systems (DGV) have been set-up in the scope of the DLT-ONERA co-operation. Both systems are capable to perform planar three component velocity measurements in air flows. The system set-up by the ONERA was designed with special regards on wind tunnel applications, while the DLR system is slightly more dedicated to turbo-machinery flows. The technical performance of these systems will be reported as well as the successful application of both systems in wind tunnel flows. DGV measurements were performed in the wake region of a car model and in the flow above a delta wing. Both measurements were cross-checked with LDA data. The common effort is now aimed at defining a concept for a DGV-system for large wind tunnels.

Barrows, T.

"SIMPLIFIED METHODS OF PREDICTING AIRCRAFT ROLLING MOMENTS DUE TO VORTEX ENCOUNTERS"

AIAA Paper 1976-0061, January 1976, Washington, DC.

Computational methods suitable for fast and accurate prediction of rolling moments on aircraft encountering wake vortices are presented. Appropriate modifications to strip theory are developed which account for the effects of finite wingspan. It is shown that in the case of an elliptic wing the aspect ratio correction to the lift curve slope should be based on the semi-span. A reciprocal theorem is used to relate the rolling moment on a wing in an arbitrary downwash field to that on a wing in steady rolling motion. Calculations are presented for a wing encountering a vortex with a Betz velocity distribution. It is shown that the ratio of the spans of the generating and encountering aircraft is the most significant parameter in determining the possible hazard.

Barrows, T. M.

"SIMPLIFIED METHODS OF PREDICTING AIRCRAFT ROLLING MOMENTS DUE TO VORTEX ENCOUNTERS"

Journal of Aircraft, Vol. 14, No. 5, May 1977, pp. 434-439

Computational methods suitable for fast and accurate prediction of rolling moments on aircraft encountering wake vortices are presented. Appropriate modifications to strip theory are developed which account for the effects of finite wingspan. It is shown that in the case of an elliptic wing the aspect ratio correction to the lift curve slope should be based on the semispan. A reciprocal theorem is used to relate the rolling moment on a wing in an arbitrary downwash field to that on a wing in steady

rolling motion. Calculations are presented for a wing encountering a vortex with a Betz velocity distribution. It is shown that the ratio of the spans of the generating and encountering aircraft is the most significant parameter in determining the possible hazard.

Barthelmie, R. J., Crippa, P., Wang, H., Smith, C. M., Krishnamurthy, R., Choukulkar, A., Calhoun, R., Valyou, D., Marzocca, P., Matthiesen, D., Brown, G. and Pryor, S. C.

"3D WIND AND TURBULENCE CHARACTERISTICS OF THE ATMOSPHERIC BOUNDARY LAYER"

Bulletin American Meteorological Society, Vol. 95, No. 5, May 2014, pp. 743-756.

The 3D wind and turbulence characteristics of the atmospheric boundary layer experiment (3D Wind) was conducted to evaluate innovative remote sensing and in situ platforms for measurements of wind and turbulence regimes. The experiment is part of a planned series that focuses on quantifying wind and turbulence characteristics at the scales of modern wind turbines and wind farms and was conducted in northern Indiana in May 2012. 3D Wind had the following specific objectives: (i) intercomparison experiments evaluating wind speed profiles across the wind turbine rotor plane from traditional cup anemometers and wind vanes on a meteorological mast and from a tethered balloon, sonic anemometers (mast mounted and on an unmanned aerial vehicle), three vertical-pointing (continuous wave) lidars and a pulsed scanning lidar, and (ii) integrate these measurements and output from 3-km-resolution (over the inner domain) simulations with the Weather Research and Forecasting Model to develop a detailed depiction of the atmospheric flow, upwind, within, and downwind of a large, irregularly spaced wind farm. This paper provides an overview of the measurement techniques, their advantages and disadvantages focusing on the integration of wind and turbulence characteristics that are necessary for wind farm development and operation. Analyses of the measurements are summarized to characterize instrument cross comparison, wind profiles, and spatial gradients and wind turbine wakes.

Barthelmie, R. J., Wang, H., Doubrawa, P. and Pryor, S. C.

"BEST PRACTICE FOR MEASURING WIND SPEEDS AND TURBULENCE OFFSHORE THROUGH IN-SITU AND REMOTE SENSING TECHNOLOGIES"

Report, July 2016, Department of Energy grant EE0005379, Cornell University, Ithaca, NY.

The purpose of this document is to briefly review some applications of in-situ and remote sensing technologies to atmospheric flow conditions in the offshore environment with a specific focus on the wind energy industry. Special emphasis is placed on providing illustrative examples of previous research, and to use those to contextualize and summarize best practice recommendations for the offshore wind energy industry, for obtaining wind speeds and turbulence characterizations.

Barthlott, C. and Fiedler, F.

"TURBULENCE STRUCTURE IN THE WAKE REGION OF A METEOROLOGICAL TOWER"

Boundary-Layer Meteorology, Vol. 108, 2003, pp. 175-190.

A meteorological tower significantly modifies the air flow, the mean wind speed and wind direction as well as the turbulence structure of the air. Such changes can be noticed in particular in the wake region of the tower. Measurements on the 200 m tower of Forschungszentrum Karlsruhe were carried out using Solent sonic anemometers in the lee of the tower and cup anemometers on both sides. In the wake region, spectral energy density is increased in the high-frequency range. Superposition of this disturbance spectrum on the undisturbed spectrum yields a 'knee' in the resulting spectrum. In the case of low turbulence intensity with stable stratification, a plateau with a constant energy content is observed in front of the knee. This effect is caused by the new production of turbulence energy from the mean flow as well as by an energy transfer from larger to smaller vortices. Power spectra in strongly stable conditions show a more rapid decrease of intensity in the region where the inertial subrange is expected. The relevant scales of wake turbulence are derived from the maximum of the disturbance spectrum. Locations of the high-frequency peak do not depend on atmospheric stability, but are controlled mainly by mean wind speed. Apart from the reduction of the mean wind speed, the spectra and cospectra exhibit a strong anisotropy for such cases. The results demonstrate the significant influence of a tower on turbulence spectra in the wake region.

Baserud, L., Flugge, M., Bhandari, A. and Reuder, J.

"CHARACTERIZATION OF THE SUMO TURBULENCE MEASUREMENT SYSTEM FOR WIND TURBINE WAKE ASSESSMENT"

Energy Procedia, Vol. 51, 2014, pp. 173-183.

The remotely piloted aircraft system (RPAS) SUMO (Small Unmanned Meteorological Observer) has been equipped with a miniaturized 5-hole probe sensor system for measurement of the 3-dimensional flow vector with a temporal resolution of 100 Hz. Due to its weight and size this system is particularly well suited for operations in the vicinity of wind turbines. To qualify for full scale measurements in turbine wakes the system has been characterized by several laboratory and field tests described in this study. A wind tunnel test against a hot-wire anemometer shows the capability of the 5-hole probe to react to turbulence in the same manner as the hot-wire system. The resulting spectra from the two platforms show in general good agreement for both laminar and turbulent flows. The 5-hole probe system can resolve turbulence up to frequencies around 20-30 Hz when using a tubing length of 15 cm between the probe and the pressure transducers. In addition, an environmental parallel test against two sonic anemometers mounted on the roof-top of a car was performed at Bergen airport Flesland. Despite several issues with the self-made and low-cost experimental setup, important system characteristics could be tested and verified. In particular the velocity spectral components of the sonic anemometer system and the 5-hole probe are in close resemblance to each other. This is at least a strong indication that the 5-hole probe is suitable for atmospheric turbulence measurements onboard the RPAS SUMO platform.

Bastankhah, M. and Porte-Agel, F.

"WIND TUNNEL STUDY OF THE WIND TURBINE INTERACTION WITH A BOUNDARY-LAYER FLOW:
UPWIND REGION, TURBINE PERFORMANCE, AND WAKE REGION"

Physics of Fluids, Vol. 29, 2017, pp. 065105-1 to 065105-18.

Comprehensive wind tunnel experiments were carried out to study the interaction of a turbulent boundary layer with a wind turbine operating under different tip-speed ratios and yaw angles. Force and power measurements were performed to characterize the variation of thrust forces (both magnitude and direction) and generated power of the wind turbine under different operating conditions. Moreover, flow measurements, collected using high-resolution particle-image velocimetry as well as hot-wire anemometry, were employed to systematically study the flow in the upwind, near-wake, and far-wake regions. These measurements provide new insights into the effect of turbine operating conditions on flow characteristics in these regions. For the upwind region, the results show a strong lateral asymmetry under yawed conditions. For the near-wake region, the evolution of tip and root vortices was studied with the use of both instantaneous and phase-averaged vorticity fields. The results suggest that the vortex breakdown position cannot be determined based on phase-averaged statistics, particularly for tip vortices under turbulent inflow conditions. Moreover, the measurements in the near-wake region indicate a complex velocity distribution with a speed-up region in the wake center, especially for higher tip-speed ratios. To elucidate the meandering tendency of far wakes, particular focus was placed on studying the characteristics of large turbulent structures in the boundary layer and their interaction with wind turbines. Although these structures are elongated in the streamwise direction, their cross sections are found to have a size comparable to the rotor area, so that they can be affected by the presence of the turbine. In addition, the study of spatial coherence in turbine wakes reveals that any statistics based on streamwise velocity fluctuations cannot provide reliable information about the size of large turbulent structures in turbine wakes because of wake meandering. The results also suggest that the magnitude of wake meandering does not depend on turbine-operating conditions. Finally, the suitability of the proper orthogonal decomposition for studying wake meandering is examined.

Batchelor, G. K.

"AXIAL FLOW IN TRAILING LINE VORTICES"

J. Fluid Mech., Vol. 20, Part 4, April 1964, pp. 645-658

A characteristic feature of a steady trailing line vortex from one side of a wing, and of other types of line vortices, is the existence of strong axial currents near the axis of symmetry. The purpose of this paper is to account in general terms for this axial flow in trailing line vortices. The link between the azimuthal and axial components of motion in a steady line vortex is provided by the pressure; the radial pressure gradient balances the centrifugal force, and any change in the azimuthal motion with distance X downstream produces an axial pressure gradient and consequently an axial acceleration. The concept of drag associated with the core of a trailing vortex is introduced, and the drag is expressed as an integral over a transverse plane which is independent of X .

Bate, Jr., E. R.

"AIRCRAFT WAKE MODELING: PRELIMINARY DESIGN ASPECTS"

AV-FR-445, August 1974, AeroVironment Inc., Pasadena, CA

The design of a scale model with a 6 ft wingspan which simulates the wake flow of a full-size airplane (B-747) is described. The wake is modeled to a full-scale downstream distance of 5 miles. The situation with respect to the simulation of wake instabilities is discussed. Only by the actual experiment that is planned for the model can the relationship between core bursting and vortex linking be established. If core bursting terminates the wake of the model too abruptly, the experimental situation might not adequately represent the full-scale case, where it is anticipated that linking due to the sinuous wake instability predominates.

Bate, Jr., E. R.

"A STUDY TO DETERMINE THE STRUCTURE OF TRAILING VORTICES FROM FULL SCALE FLIGHT TEST DATA"

AV-FR-441, July 1974, AeroVironment Inc., Pasadena, CA

Computerized data reduction techniques were applied to high resolution velocity measurements obtained during full-scale aircraft wake probing experiments. The desired results were the determination of vortex circulation and core size as a function of wake age. Data scatter prevented the desired results from being fully achieved; it is suggested that the data scatter represents real effects and that these effects are produced by turbulence.

Batemen, C. D., Hruby, J. and Conner, K. J.

"AIRCRAFT WEATHER INFORMATION SYSTEM"

US Patent 6,043,756, March 2000.

A system and method for downlinking weather data, generated by existing weather and data sensors, to a ground station. The ground station utilizes data from multiple aircraft to form refined weather information, and uplinks the refined weather information to the aircraft. The refined weather information is stored at the aircraft and picture generating equipment, such as an existing onboard ground proximity terrain picture and symbol generator, generates pictorial information depicting weather. The pictorial information is displayed, for example, by an existing EFIS or weather radar display, in the form of polygons.

Bates, Jr., G. P.

"A SELECTED BIBLIOGRAPHY PERTAINING TO THE AIRCRAFT WAKE VORTEX PROBLEM"

AGARD, Symposium on Flight in Turbulence, Bedfordshire, England, May 1973

A bibliography pertaining only to available papers directly concerning the development of a trailing vortex flow behind an aircraft and the effects of this flow on a following aircraft.

Battam, N. W., Gorounov, D. G., Korolev, G. L. and Ruban, A. I.

"SHOCK WAVE INTERACTION WITH A VISCOUS WAKE IN SUPERSONIC FLOW"

J. Fluid Mech., Vol. 504, 2004, pp. 301-341

A theoretical investigation of the breakdown of the viscous wake downstream of a flat plate in supersonic flow is performed in this paper based on the large Reynolds number asymptotic analysis of the Navier-Stokes equations. The breakdown is provoked by an oblique shock wave impinging on the wake a small distance downstream of the plate trailing edge. Two flow regimes are considered. In the first case, the shock impinges on the wake within the region of viscous-inviscid interaction that is known to occupy a vicinity of the trailing edge. Under these conditions the interaction process may be described by the equations of the triple-deck theory. To obtain a numerical solution of these equations we used a rapid matrix Thomas technique in conjunction with Newton iterations. The results of the calculations not only predict the wake breakdown near the shock location but also reveal a hysteresis behavior of the flow as the shock is moved downstream, giving rise to three solution branches. The second part of the paper is concerned with the flow regime when the shock interacts with the wake further downstream of the trailing edge triple-deck region. In this case the fluid motion proves to be inviscid to leading order not only in the upper deck of the interaction region but also everywhere inside the wake. Due to this simplification the interaction problem can be reduced to a single integro-differential equation governing the pressure distribution along the interaction region. With known pressure the Bernoulli equation may be used to find the velocity field. The Bernoulli equation also allows us to formulate a simple criterion which may be used to predict the onset of wake breakdown. We found that viscosity becomes important again in a smaller vicinity of the breakdown point where the flow reversal takes place. It is remarkable that the viscous-inviscid interaction problem governing the flow in this vicinity admits an analytical solution.

Batterson, J. W., Maicke, B. A. and Majdalani, J.

"ADVANCEMENTS IN THEORETICAL MODELS OF CONFINED VORTEX FLOWFIELDS"

2007 JANNAF Propulsion Meeting, May 2007, Denver, CO.

In this article, we review some of the theoretical solutions used to describe swirl dominated flows in both unidirectional and bidirectional flow orientations. This short survey starts with the Rankine vortex and culminates in the presentation of a compressible solution of the bidirectional vortex. After classifying representative swirl motions as external or internal depending on physical boundary conditions, their commonalities are identified along with their relevance to either geophysical or industrial applications. For example, all swirl dominated flows comprise a forced vortex core centered around their axis of rotation. The core is due to viscous forces and increases in size with successive

increases in viscosity. It is delineated by the point where the swirl velocity reaches its maximum. Within the forced vortex core, the tangential velocity is linearly proportional to the radius, a characteristic of rigid body rotation. Outside the forced vortex core, the tangential velocity gradually becomes inversely proportional to the radius, thus exhibiting a free vortex tail. In internal flows, this free, irrotational tail is clipped at the boundaries in fulfillment of the no slip requirement. In external flows, it extends out to infinity. Finally, all swirl dominated flows decay axially and their vorticity is confined to either the core vortex or wall boundary layers. These will be described in the context of the bidirectional vortex confined in a cylindrical chamber. What is most prevalent here, and perhaps, what sets the analysis of the bidirectional vortex apart lies in its true prediction of essential flow attributes directly from first principles. Unlike other studies that require conjecture or post-diction, for example, in estimating or adjusting the maximum swirl velocity and thickness of the core vortex to fit a given flow pattern (e.g., the Rankine vortex), these are obtained directly from the asymptotic solution of the tangential boundary layer equation for the bidirectional vortex. We also identify the key similarity parameters that control the problem, including the inflow parameter and the vortex Reynolds number. The latter combines the mean flow Reynolds number and the product of the swirl number and chamber aspect ratio. In this study, the core and sidewall boundary layers are quantified as function of the vortex Reynolds number. The compressible solution is also obtained assuming a Rayleigh-Janzen expansion in the inflow Mach number squared.

Bauer, L. A.

"THE RELATION BETWEEN POTENTIAL TEMPERATURE AND ENTROPY"

Physical Review (Series I), Vol. 26, Issue 2, February 1908, pp. 177-183

A historical account of the concept as well as the modern-day terminology of potential temperature is given. The relationship between potential temperature and entropy is then derived and illustrated in the context of a perfect gas. It is shown that as far as a perfect gas is concern, it is possible to express the entropy function in its simplest form as the potential temperature function. As such, if the entropy is increased, the potential temperature is likewise increased. If the entropy remains constant, then the potential temperature would remain constant. Owing to the intimate relationship between entropy and potential temperature the term 'entropic temperature' has been proposed by the author.

Bauer, M., Grund, T., Nitsche, W. and Ciobaca, V.

"WING TIP DRAG REDUCTION AT NOMINAL TAKE-OFF MACH NUMBER: AN APPROACH TO LOCAL ACTIVE FLOW CONTROL WITH A HIGHLY ROBUST ACTUATOR SYSTEM"

Aerospace, Vol. 3, 2016, pp. 36-1 to 36-18.

This paper discusses wind tunnel test results aimed at advancing active flow control technology to increase the aerodynamic efficiency of an aircraft during take-off. A model of the outer section of a representative civil airliner wing was equipped with two-stage fluidic actuators between the slat edge and wing tip, where mechanical high-lift devices fail to integrate. The experiments were conducted at a

nominal take-off Mach number of $M = 0.2$. At this incidence velocity, separation on the wing section, accompanied by increased drag, is triggered by the strong slat edge vortex at high angles of attack. Based on global force measurements and local static pressure data, the effect of pulsed blowing on the complex flow is evaluated, considering various momentum coefficients and spanwise distributions of the actuation effort. It is shown that through local intensification of forcing, a momentum coefficient of less than 0.6 percent suffices to offset the stall by 2.4 degrees, increase the maximum lift by more than 10 percent and reduce the drag by 37 percent compared to the uncontrolled flow.

Bauer, T., Vechtel, D., Abdelmoula, F. and Immisch, T.

"IN-FLIGHT WAKE ENCOUNTER PREDICTION WITH THE WAKE ENCOUNTER AVOIDANCE AND ADVISORY SYSTEM"

AIAA Paper 2014-2333, June 2014, Atlanta, GA.

DLR is working on a Wake Encounter Advisory & Avoidance (WEAA) system to allow pilots to avoid potentially dangerous wake vortex encounters by a tactical evasion maneuver. Such maneuver is of small scale i.e. it tries to adhere to the planned flight track as closely as possible and is not intended to require ATC permission. The paper introduces system design and core functions of the WEAA system (meteorological data fusion, wake vortex prediction, trajectory prediction and conflict detection, hazard evaluation, avoidance trajectory generation, alerting and guidance) and briefly describes DLR's technical solutions. Initial results will be presented for the system implementation including first results from recent flight tests for on-board conflict detection employing DLR's Falcon 20E and A320 Advanced Technology Research Aircraft (ATRA).

Bauknecht, A., Ewers, B., Wolf, C., Leopold, F., Yin, J. and Raffel, M.

"THREE-DIMENSIONAL RECONSTRUCTION OF HELICOPTER BLADE-TIP VORTICES USING A MULTI-CAMERA BOS SYSTEM"

Experiments in Fluids, Vol. 56, 2015, pp. 1866-1 to 1866-13.

Noise and structural vibrations in rotorcraft are strongly influenced by interactions between blade-tip vortices and the structural components of a helicopter. As a result, knowing the three-dimensional location of vortices is highly desirable, especially for the case of full-scale helicopters under realistic flight conditions. In the current study, we present results from a flight test with a full-scale BO 105 in an open-pit mine. A background-oriented schlieren measurement system consisting of ten cameras with a natural background was used to visualize the vortices of the helicopter during maneuvering flight. Vortex filaments could be visualized and extracted up to a vortex age of 360 degrees. Vortex instability effects were found for several flight conditions. For the camera calibration, an iterative approach using points on the helicopter fuselage was applied. Point correspondence between vortex curves in the evaluated images was established by means of epipolar geometry. A three-dimensional reconstruction of the main part of the vortex system was carried out for the first time using stereophotogrammetry. The reconstructed vortex system had good qualitative agreement with the

result of an unsteady free-wake panel method simulation. A quantitative evaluation of the 3D vortex system was carried out, demonstrating the potential of the multi-camera background-oriented schlieren measurement technique for the analysis of blade-vortex effects on rotorcraft.

Bauknecht, A., Merz, C. B. and Raffel, M.

"AIRBORNE APPLICATION OF THE BACKGROUND ORIENTED SCHLIEREN TECHNIQUE TO A HELICOPTER IN FORWARD FLIGHT"

17th International Symposium on Application of Laser Techniques to Fluid Mechanics, July 2014, Lisbon, Portugal.

Blade-tip vortices and their interaction with the helicopter blades play an important role in the generation of noise on rotorcrafts. Full-scale vortex visualization is essential for the understanding of these effects and the validation of sub-scale experiments and numerical simulations. In the present work, the reference-free Background Oriented Schlieren (BOS) method was used to visualize blade-tip vortices of a full-scale BO 105 helicopter. Two flight tests were conducted with a dual-camera BOS system. In the first experiment, the ground-based camera was tested on the helicopter in hovering flight with an artificial background pattern. The main and tail rotor tip vortices and the exhaust gases from the helicopter engines were visualized during take-off and hovering flight. Main rotor tip vortices up to a vortex age of 450 degrees, vortex instability effects and interactions with the tail boom were detected. In the second flight test, a modified version of the dual-camera BOS was used to visualize the main rotor blade-tip vortices of the BO 105 during forward, curve and accelerating forward flight with velocities over the ground of 60-80 knots. The camera system was deployed aboard a microlight airplane flying above and to the side of the helicopter with fields and meadows serving as natural backgrounds. It was shown that, during curve flight, vortices up to a maximum vortex age of 630 degrees at distances of up to one rotor diameter behind the rotor plane could be visualized in some parts of the rotor wake. For accelerating forward flight, blade-vortex interaction effects and deformations of the vortex system were observed. In general, vortex visibility varied greatly between different parts of the rotor wake and different measurement images. This mainly resulted from the background noise level, which can vary based on the suitability of the natural background for the BOS method. A variety of natural backgrounds was analyzed and compared to the artificial dot pattern used for the hover test. Image contrast, homogeneity and structure size were found to vary between different natural backgrounds and to be significantly lower than for the artificial background pattern, but still within a useable range. The visualization results obtained during the inflight measurements show that the reference-free BOS method is highly suitable for the detection of helicopter blade-tip vortices during full-speed forward and maneuvering flight, therefore removing the restrictions imposed by ground-based measurements.

Bauknecht, A., Merz, C. B., Raffel, M., Landolt, A. and Meier, A. H.

"BLADE-TIP VORTEX DETECTION IN MANEUVERING FLIGHT USING THE BACKGROUND-ORIENTED SCHLIEREN TECHNIQUE"

Journal of Aircraft, Vol. 51, No. 6, November-December 2014, pp. 2005-2014.

The background-oriented schlieren technique was used to visualize the blade-tip vortices of a Eurocopter AS532UL Cougar helicopter in maneuvering flight. The test program covered a large part of the flight envelope, including maneuvers such as hover flight, fast forward flight, flare maneuvers, and high-speed turns. For selected flight conditions, the aerodynamic results are presented here. It is shown that, with the reference-free background-oriented schlieren method, the detection of vortex filaments up to vortex ages of 540 deg is possible. The visualization of the vortex system is used to detect aerodynamic phenomena such as blade-vortex interactions, vortex-airframe interactions, and the occurrence of smooth sinuous disturbances. A detailed description of the applied reference-free background-oriented schlieren setup is given, and the suitability of different natural backgrounds for the background-oriented schlieren method is analyzed.

Bauknecht, A., Raffel, M. and Grebing, B.

"AIRBORNE ACQUISITION OF BLADE TIP DISPLACEMENTS AND VORTICES ON A COAXIAL ULTRALIGHT HELICOPTER"

AIAA Paper 2017-3552, June 2017, Denver, CO.

A series of comprehensive flight tests investigated the flight dynamics and explored the flight envelope of a newly developed ultralight, coaxial, counter-rotating helicopter from the company EDM Aerotec. The present paper focuses on optical measurement techniques that were applied to study the minimum blade tip clearance and convection of blade tip vortices around the dual-rotor system. A calibrated single-camera system was used to quantify the movement and distances of the blade tip at a critical rotor azimuth for multiple steady and unsteady flight maneuvers. The measurements allowed critical flight conditions to be identified and provided flight data for the validation of comprehensive rotor codes. In an additional flight test, an airborne background-oriented schlieren (BOS) system was operated aboard a second helicopter to visualize the blade tip vortices of the ultralight helicopter in forward flight. The BOS measurements resulted in the first visualization of blade-vortex and vortex-structure interaction effects on a full-scale coaxial helicopter. The application of optical measurement systems in the present flight tests gives valuable insight into the aerodynamics and blade dynamics of a free-flying counter-rotating helicopter and demonstrates how these methods can effectively support the development process of new rotorcraft.

Baumann, R. and Gerz, T.

"LARGE-EDDY SIMULATIONS OF TWO DISTURBED COUNTER-ROTATING VORTEX PAIRS"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

Our simulations corroborate the idea that a system of two counter-rotating vortex pairs provides a desirable vorticity distribution behind an aircraft since such a system can be triggered to lose vortex coherence and circulation quickly. Properly 'injected' disturbances lead to the evolution of azimuthal and vertical structures of secondary vorticity which interacts with the primary vortices, resulting in a

quick decay of all coherent vortices into incoherent turbulence in the late mid to early far field. This, in turn, effectively diminishes the induced rolling moment experienced by a wake-encountering aircraft. The problem, though, remains to find robust and controllable disturbance mechanisms which yield the desired effects. Especially the differences between high turbulence forcing and low turbulence forcing cases underline the importance of a correct 'timing'.

Baumgardner, D., Miake-Lye, R. C., Anderson, M. R. and Brown, R. C.

"AN EVALUATION OF THE TEMPERATURE, WATER VAPOR, AND VERTICAL VELOCITY STRUCTURE OF AIRCRAFT CONTRAILS"

Journal of Geophysical Research, Vol. 103, No. D8, April 1998, pp. 8727-873.

Measurements made in contrails formed in the wake of a Lear 35 have been analyzed with respect to their temperature, water vapor, and vertical velocity structure. The National Center for Atmospheric Research (NCAR) Sabreliner traversed the Lear's wake at distances varying from 150 m to 5 km and penetrated the contrails 243 times over the course of seven flights. The width of the plume is documented as a function of the distance between the leading and chase aircraft and the temperature, humidity and vertical motion components inside the plume have been analyzed and compared with a three-dimensional wake vortex model. The analysis shows that the width increases very little within the first 5 km, in agreement with the vortex model. The increases in temperature and water vapor in the contrail 500 m from the exhaust were nearly equal to 0.6 degrees and 8 ppmv, respectively. The vertical velocity change across the contrail was nearly equal to 4 m/s. The agreement between observations and model predictions is quite good in comparisons of temperature. The model predicts larger water vapor mixing ratios, but the differences can be explained within the expected measurement uncertainties and lack of particle condensation in the vortex model. The model predicts larger excursions in vertical velocity but the trends are in excellent agreement between model and observations.

Baxley, B. T., Barmore, B. E., Abbott, T. S. and Capron, W. R.

"OPERATIONAL CONCEPT FOR FLIGHT CREWS TO PARTICIPATE IN MERGING AND SPACING OF AIRCRAFT"

AIAA Paper No. 2006-7722, Wichita, KS, Sept. 2006

The predicted tripling of air traffic within the next 15 years is expected to cause significant aircraft delays and create a major financial burden for the airline industry unless the capacity of the National Airspace System can be increased. One approach to improve throughput and reduce delay is to develop new ground tools, airborne tools, and procedures to reduce the variance of aircraft delivery to the airport, thereby providing an increase in runway throughput capacity and a reduction in arrival aircraft delay. The first phase of the Merging and Spacing Concept employs a ground-based tool used by Air Traffic Control that creates an arrival time to the runway threshold based on the aircraft's current position and speed, then makes minor adjustments to that schedule to accommodate runway

throughput constraints such as weather and wake vortex separation criteria. The Merging and Spacing Concept also employs arrival routing that begins at an en route metering fix at altitude and continues to the runway threshold with defined lateral, vertical, and velocity criteria. This allows the desired spacing interval between aircraft at the runway to be translated back in time and space to the metering fix. The tool then calculates a specific speed for each aircraft to fly while enroute to the metering fix based on the adjusted land timing for that aircraft. This speed is data-linked to the crew who fly this speed, causing the aircraft to arrive at the metering fix with the assigned spacing interval behind the previous aircraft in the landing sequence.

Baxter, R. A.

"A SIMPLE STEP BY STEP METHOD FOR THE ALIGNMENT OF WIND SENSORS TO TRUE NORTH"

11th Symposium on Meteorological Observations and Instrumentation, Paper 1.2, January 2001, Albuquerque, NM.

The alignment of wind sensors to a known direction has traditionally presented a challenge to even the most experienced user. The common thread for most alignment methods is to use the reference to true north. Once this reference direction is accurately determined, the alignment of the wind sensor is adjusted either in software programming or with the hardware to read north or 0 degrees. It is the determination of that true north direction that has been the subject of discussions and development of various methodologies. This paper discusses some of the problems associated with the determination of true north using magnetic methods and traces the history of the presented methodology development. While not intended as a ground breaking technology, the presented method serves to establish a consistent set of procedures that will provide individuals responsible for the setup and verification of wind measurement equipment with a clear, unambiguous and repeatable method for sensor alignment.

Bazin, M. F.

"TRAJECTORY OF A PARTICLE RELEASED IN THE WAKE OF AN AIRCRAFT"

M.S. Thesis, May 1982, Mass. Institute of Technology, Cambridge, MA

In aerial spraying the trajectory of the spray droplets is affected by the aerodynamic wake of the aircraft. Analytical studies were carried out to assess the effect of the trailing vortices on the trajectory of a particle. The particles that are initially released in the wing-tip vortices are entrained by the wake until either the particles escape from its influence or the vortices weaken sufficiently to allow gravity to dominate the dispersion of the particles. The effect of the ground boundary layer on the vortex center trajectory is investigated and is shown to cause an upward displacement of the trajectory. However, this is too small an effect to explain the vortex rebound phenomenon. The equations of motion for a particle in a line vortex are derived. A dimensional analysis of these equations is carried out and computational models are given in specific domains. Particularly, in the Stokes' flow regime a mathematical description of great computational simplicity is derived.

Beard, J. E. and Takahashi, T. T.

"(UN)CONTROLLED FLIGHT INTO TERRAIN: A HISTORY OF OBSTACLE CLEARANCE REGULATIONS"

AIAA Paper 2018-1614, January 2018, Kissimmee, FL.

Because aviation is comprehensively regulated, commercial flying is safer than it ever was before. This was not the case during the early years of aviation. Back in the early 1930's, only limited regulations governed takeoff distance (land-based aircraft were expected to takeoff in less under 1000-ft) and all-engines-operating climb (the 'Rule of Eight' which required aircraft to have an all-engines operative climb rate (in ft/min) of eight times its stall speed (in knots)). In this paper, we make a historical inquiry into the evolution of regulations governing the takeoff obstacle clearance problem. We show that the FAA, and its predecessor agencies, typically establish and amend Federal Aviation Regulations on a reactionary -- not proactive -- basis after high profile crashes. We trace amendments to key regulations governing the obstacle clearance problem to specific air accidents where insufficient climb performance was deemed as the probable cause of death.

Bearman, P. and Hogan, C.

"EXPERIMENTS ON WAKE VORTEX CONTROL"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

This presentation is concerned with a laboratory investigation of trailing vortices and use is made of a water tank to visualize flow structure. Measurements of velocity and vorticity fields, at a series of downstream stations, are being made in a wind tunnel using PIV. The initial experiments have been performed using a delta wing with a 75-degree leading edge sweep, i.e. 30-degree apex angle. It is planned to move to a typical transport aircraft wing configuration soon. Disturbances are introduced in two ways: by adding a harmonic variation to the relative flow speed and by adding a sinusoidal perturbation to the wing incidence. Flow visualization is carried out in the water tank using fluorescent dye and a light beam from an argon ion laser. The beam passes through a set of optics to produce a near constant thickness sheet running the length of the tank. After the wing has traversed the tank the trailing vortices continue to interact and the flow is studied until the vortex structure has apparently broken down. Some caution has to be observed because dye is being viewed and not vorticity. In some experiments one trailing vortex was visualized with green dye and the other with red dye to obtain a clearer picture of the interaction process. Some video sequences of the flow visualization will be shown. Initially the short wavelength instability is clearly visible but as the flow evolves the well-known Crow, or long wavelength, instability develops. The time to the point where one vortex appears to wrap around the other is termed the breakdown point. This time is then transformed into an equivalent distance behind the wing, which in the present case is about 110 wing spans downstream. For a 75-degree delta wing the wavelength of the Crow instability, as shown in previous studies, is around $4.6b$, where b is the initial distance between the trailing vortices. If the flow speed is perturbed at this wavelength then the trailing vortices are found to breakdown closer to the wing. However, if the wavelength is smaller or larger than the Crow value by some critical amount the breakdown point

moves further downstream and the imposed disturbance decays before the Crow instability develops. It is clear, therefore, that if artificial disturbances are to be introduced it is important that the wavelength is carefully controlled. Further results using incidence variation will be shown, together with PIV measurements.

Bearman, P., Heyes, A., Lear, C. and Smith, D.

"NATURAL AND FORCED EVOLUTION OF A COUNTER ROTATING VORTEX PAIR"

Experiments in Fluids, Vol. 40, 2006, pp. 98-105

Naturally occurring instabilities such as the long wave Crow instability are one of the mechanisms that can bring about the break-up of aircraft wake vortex pairs. Encouraging the early onset of such instabilities by active or passive means offers the possibility of accelerating wake break-up of aircraft wake vortex pairs. Encouraging the early onset of such instabilities by active or passive means offers the possibility of accelerating wake break-up and dissipation with favorable consequences in terms of safe aircraft separation and airport capacity. This paper describes an experimental investigation of the evolution of the Crow instability in a counter rotating vortex pair perturbed by a pulsed air sheet. Flow measurements were made using two-dimensional particle image velocimetry and two methods devised to detect wake break-up from the two-dimensional data. Pulsed excitation at a wavelength within the range amplified by the Crow instability resulted in wake break-up and the formation of vortex rings at a downstream distance reduced by up to 37% compared to the baseline case. For excitation at a wavelength outside the excited range early break-up was also observed but the extent of the accelerated break-up was reduced as the amplitude of the excitation was increased.

Bearman, P., Heyes, A., Lear, C. and Smith, D.

"EVOLUTION OF A FORCED COUNTER ROTATING VORTEX PAIR FOR TWO SELECTED FORCING FREQUENCIES"

Experiments in Fluids, Vol. 43, 2007, pp. 501-507

In this paper, results from an experimental study of the natural and forced evolution of a pair of counter rotating wing-tip vortices are reported. The vortices were generated using a pair of opposed wing-tips in a wind tunnel and measurements made up to 77 tip-spacings downstream of the models at a chord Reynolds number of $1.3 \times 100,000$. The wake was interrogated using 2D particle image velocimetry and the long-wave Crow instability observed. Velocity data were recorded throughout the lifetime of the instability from initial growth through linking, formation of vortex rings and their subsequent decay. Forcing was achieved using pulsed air jets blowing in the span-wise direction from the wing tip and imparting spatially periodic perturbations to the vortices. Forcing at a frequency within the range amplified by the Crow instability was found to enhance the instability growth rate whereas forcing at a frequency outside the amplified range was found to inhibit instability growth. In the latter case the imparted wavelength was observed to die out with a preferred wavelength growing in its place.

Beasley, G. D.

"SYSTEM AND METHOD FOR CREATING VISUAL IMAGES OF AIRCRAFT WAKE VORTICES"

US Patent 5,845,874, December 1998

A system and method for creating visual images of aircraft wake vortices allows a user, such as an aircraft controller, to increase several airport transactions while maintaining a predetermined level of safety. Wake vortices are simulated in a three-dimensional environment considering various aircraft, environmental, and atmospheric conditions. The simulated wake vortices are rendered from a perspective selectable by the user. The displayed image allows the user to direct aircraft around potentially harmful wake vortices.

Beaumier, P. and Delrieux, Y.

"DESCRIPTION AND VALIDATION OF THE ONERA COMPUTATIONAL METHOD FOR THE PREDICTION OF BLADE-VORTEX INTERACTION NOISE"

Aerospace Science and Tech., Vol. 9, 2005, pp. 31-43

The computational method used at ONERA for the prediction of Blade-Vortex Interaction noise is presented in this paper. The five steps of the computational chain are first described. The calculations are then validated by comparison with two different databases. The first one was obtained in the HART program; in this case, it is shown that the influence of Higher Harmonic Control on wake geometry and radiated noise is well captured. The second one was obtained in the ERATO program, where a passive blade shape optimization was done: in this case, the calculations succeed in predicting the relative difference in noise levels between the ERATO optimized blade compared to a reference blade, although the wake geometry of the ERATO rotor is not well captured. Finally, strategies to reduce the BVI noise for blades equipped with trailing-edge flaps are proposed.

Becu, E. and Pavlov, V.

"EVOLUTION OF CONFIGURATIONS OF VORTICES WITH THE SAME GLOBAL INTEGRAL INVARIANTS"

Comptes Rendus Mecanique, Vol. 332, Issue 10, October 2004, pp. 835-840

In this Note, we address the question of the evolution of a distribution of N identical localized vortices. Using direct numerical simulation, (here the Runge-Kutta scheme of order 4), together with the localized vortices model, we show that different initial distributions of vorticity with identical integral invariants may exist. We show that the initial configurations with the same invariants may evolve to totally different quasi-final states.

Bedard Jr., A. J.

"LOW-FREQUENCY ATMOSPHERIC ACOUSTIC ENERGY ASSOCIATED WITH VORTICES PRODUCED BY THUNDERSTORMS"

Monthly Weather Review, Vol. 133, No. 1, January 2005, pp. 241-263.

An infrasonic observatory collocated with the Colorado State University CHILL radar during the summer of 1995 permitted unique comparisons between severe storm kinematics and detected acoustic energy at subaudible frequencies near 1 Hz. Radar observations of a velocity couplet aloft (evolving into a tornado) showed a circulation maximum descending for about 30 min while moving to the east. The detected infrasound followed the trend of these observations. A model of sound radiated from vortex systems predicts frequencies in the range observed. These data are interpreted in the context of past infrasonic observations. An ongoing study comparing regional tornado and funnel sightings with archived infrasonic data has identified over 100 cases to date where the infrasonic signals occurred at the time of, and from the direction of, the vortices. For some of these cases, the distances were greater than 100 km. The author and his associates continue to collect datasets to permit further evaluation of infrasonic detection methods.

Bedard, Jr., A. J.

"THE DYNAMICS OF ATMOSPHERIC AND INDUSTRIAL VORTICES"

Ph.D. Thesis, 1982, University of Colorado, Boulder, CO

This thesis reviews observed properties of a wide range of atmospheric vortices on scales from aircraft wake vortices (meters) to hurricanes (100's of kilometers). Common properties for atmospheric and industrial vortices (such as the forms of distant tangential flow fields) are documented as well as differences (such as effective generation mechanisms and core sizes). Analytical and numerical calculations predict features (e.g., decay, motions, pressure fields, and instabilities) for a variety of situations (e.g., isolated vortices, multiple vortices, and vortex sheets). Two models representing a line vortex and a line swirl are contrasted in comparing features of rotating flows. A review of complicating factors such as 2-dimensional instabilities, boundary layer effects, axial flows, 3-dimensional instabilities, and turbulence indicates the difficult problems posed for the execution and interpretation of full-scale atmospheric measurements. Experimental data taken for aircraft vortices are used to underline these problems and also demonstrate areas where analytical results are clearly applicable. A flexible apparatus designed for the generation and study of vortices in the laboratory is described. This water tank system utilizing the starting vortices behind airfoils of known characteristics offers wide possibilities for studying vortices under controlled conditions, overcoming many of the limitations of past techniques.

Bedard, Jr., A. J.

"MEASUREMENTS OF AN AIRCRAFT WAKE VORTEX SYSTEM USING A METEOROLOGICAL TOWER"

Proceedings 9th Conf. on Aerospace and Aeronautical Meteorology, American Meteorological Society, Omaha, NE, June 1983, pp. 252-256

The experiment for the data presented here involved flybys near the Boulder Atmospheric Observatory (BAO), which provided real-time outputs of various parameters, including wind speed, wind direction, and temperature. These data are used to predict the motion of the vortex system and to guide the aircraft height, bearing, and position in relation to the tower and the radar. The results of the experiment, which focused chiefly on the evaluation of an FM/CW radar for wake vortex detection, are seen as providing an interesting case study of vortex impingement upon a well-instrumented meteorological tower. The horizontal and vertical wind speed measurements are compared with those expected from the passage of a wake vortex system. The temperature perturbation obtained gives a data set indicating the temperature distribution in a wake vortex system.

Bedard, Jr., A. J.

"THE USE OF REMOTE SENSORS AND LABORATORY SCALE MODELS IN WAKE VORTEX ADVISORY SYSTEMS"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 50-1 - 50-22

Wake vortex advisory systems require improved definition of wind, temperature and turbulence profiles at airports. For example, in light wind situations a vortex can remain in the vicinity of a runway, not moving under ground-effect to a safe location. Also, the wake vortex vertical position and decay is influenced by vertical profiles of temperature and turbulence, as well as the presence of organized atmospheric structures (such as thermal plumes and gravity/shear waves). More knowledge is required about the three-dimensional structure of the atmosphere for operational use. As closer aircraft spacings become practical, interactions between wakes of different aircraft will become more likely with the result that a variety of unusual propagation paths could result. Such potential interactions, as well as the important effects of vertical atmospheric structure changes on individual wakes, make real-time monitoring of the airport lower atmospheric boundary layer a critical need. This paper addresses two main topics. Initial sections describe newly available remote profiling technologies capable of fulfilling these measurement needs with potential for contributing to other airport requirements, such as microburst and icing forecasting, low-level wind measurement, and enhancing wind shear monitoring capabilities. The second topic reviews ways that laboratory scale model experiments can help improve our knowledge of wake vortex instabilities, transport, and decay. Finally, potential applications of integrated remote sensing systems are reviewed in the context of verifying laboratory experiments for test bed experiments as well as operational environments.

Bedard, Jr., A. J. and Cook, R. K.

"PRESSURE FIELDS FROM AIRCRAFT AND LOCALIZED SEVERE WEATHER AS BUILDING DESIGN PARAMETERS"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 25, 1987, pp. 355-363

We observe that aircraft produce pressure increases at the surface proportional to the aircraft weight. Measured values are in general agreement with predictions. The time scales are longer for aircraft weight transfer pressure changes (typically 2-4 s, than for acoustic shock waves related to supersonic flight (typically 0.1-0.3 s). However, the amplitudes (typically from 0.1-1 mbar) are comparable. Summaries of observed aircraft pressure transients together with pressure measurements for thunderstorm gust fronts, downflows, and tornadoes should serve as a resource for investigating structure designs under a variety of conditions of atmospheric loading.

Beeler, D. E. and Gerard, G.

"WAKE MEASUREMENTS BEHIND A WING SECTION OF A FIGHTER AIRPLANE IN FAST DIVES"

NACA TN-1190, March 1947, Langley Aeronautical Lab., Langley Field, VA

Wake measurements made in a vertical plane behind a wing section of a fighter airplane are presented for a range of Mach number up to 0.78. Since evidences of reverse flow were found in a large part of the surveys - possibly because of interference of the rake support - the computed profile-drag coefficients are considered to be only qualitative. The results showed that the large increase in drag coefficient beyond the critical Mach number indicated by wind-tunnel tests was also obtained under flight conditions and that the wake width was extended sharply when shock was encountered. The wake extension occurred first at the upper surface since the highest local velocity was obtained on that surface. The large increase in drag coefficient for the wing section tested did not occur until after the critical Mach number had been exceeded by approximately 0.05. Comparison of the profile-drag measurements with total airplane drag measurements showed that the large increases in drag in both cases started to occur at the same value of Mach number. The results further indicated that wake measurements made in three-dimensional flow after shock had occurred cannot, in general, be interpreted in terms of section profile-drag coefficient because of the existence of the strong lateral flow indicated by tuft behavior in the dead-air region behind the shock.

Belano, J. C.

"C-17/PARATROOPER RISK ASSESSMENT ANALYSIS"

M.S. Thesis, March 1997, Air Force Inst. of Tech., Wright-Patterson AFB, OH

The C-17 test and evaluation community has been testing different aircraft formation geometries in search of a configuration which minimizes paratrooper encounter with the wake vortices of upstream aircraft. This thesis develops a simulation tool that the C-17 test and evaluation community can utilize as an advanced risk assessment model to use on proposed formation geometries prior to live testing. The model is developed under the architecture of object-oriented simulation using MODSIM III and parallels similar efforts by the Aerodynamic Decelerator Technology community in creating object-oriented counterparts to already developed trajectory models of various degrees of freedom. This thesis develops the paratrooper object portion of the simulation model while the Petry thesis (1997) develops the C-17 aircraft and vortex objects. Once integrated with the Petry C-17 aircraft and vortex

objects, and after verification and validation, the simulation model is applied to a simplified airborne operation scenario using the mean distance of paratrooper impact location to assembly areas and DZ dispersal distribution as MOEs for different aircraft formation geometries. Lateral separation is shown to have the most influence on both MOEs, while trail distance has minimal effects. For the airborne commander, this translates into operational parameters applicable to the choice of assembly areas and formation geometries. Further operational parameters of any significance are gained when coupled with the results from Petry on encounter rates between paratroopers and wake vortices where trail distance has a significant impact.

Belcastro, C. M. and Foster, J. V.

"AIRCRAFT LOSS-OF-CONTROL ACCIDENT ANALYSIS"

AIAA Paper 2010-8004, August 2010, Toronto, Ontario, Canada.

Loss of control remains one of the largest contributors to fatal aircraft accidents worldwide. Aircraft loss-of-control accidents are complex in that they can result from numerous causal and contributing factors acting alone or (more often) in combination. Hence, there is no single intervention strategy to prevent these accidents. To gain a better understanding into aircraft loss-of-control events and possible intervention strategies, this paper presents a detailed analysis of loss-of-control accident data (predominantly from Part 121), including worst case combinations of causal and contributing factors and their sequencing. Future potential risks are also considered.

Beljaars, A. C. M.

"THE MEASUREMENT OF GUSTINESS AT ROUTINE WIND STATIONS - A REVIEW"

World Meteorological Organization Report No. 31, 1987, Royal Netherlands Meteorological Institute, De Bilt, The Netherlands.

Many meteorological stations observe wind gusts on a routine basis. The measuring procedures, however, are far from uniform. Some stations measure 'instantaneous gusts' with fast response equipment, whereas other stations report the fastest mile. In this report it is tried to unify the observation practice by formulating specifications for the measurement of wind gustiness. The user requirements are reviewed and the consequences for the measuring system are discussed. Two aspects play an important role in this problem. First of all, it is important to observe wind extremes in a uniform way and such that the results can be used directly in wind load studies. Secondly, gustiness measurements, can be used to characterize the exposure error of wind stations. The gustiness of the wind is a measure of the turbulence intensity which is directly related to the roughness of the upstream terrain. This information enables the correction of mean wind observations for local perturbations. Application of such procedures would greatly enhance the quality of surface wind observations over land. The best gustiness parameters for this application are the standard deviation of wind speed and wind direction. It is therefore recommended to measure these parameters on a routine basis with the new generation of wind measuring systems.

Bell, J. H. and Mehta, D.

"INTERACTION OF A STREAMWISE VORTEX WITH A MIXING LAYER"

Phys. Fluids A, Vol. 2, No. 11, November 1990, pp. 2011-2023

An experimental study has been conducted on the interaction of a single streamwise vortex with a plane turbulent mixing layer. The vortex was generated by a half-delta wing mounted in the settling chamber of a blower-driven wind tunnel. The single-stream mixing layer originated from the top lip of the extended contraction exit, with a tripped initial boundary layer. Initially, the vortex rode below the mixing layer and its effect was to locally distort the mean velocity and Reynolds stress distributions in the lower (high-speed) side of the mixing layer. Once the vortex became embedded within the mixing layer, the distortion, which took the form of a wrinkle, spread through the whole width of the layer. The induced extra strain rates in the mixing layer resulted in the generation of additional, relatively large, Reynolds stresses in the regions around the vortex. In particular, the secondary shear stress reached a maximum absolute value equivalent to about 40% of the maximum primary shear stress, thus indicating significantly increased three-dimensionality in the mixing layer. The vortex appeared to decay rapidly once it was embedded in the mixing layer; the maximum mean streamwise vorticity was observed to decay as approximately $1/(X^2)$ in this region. By the last measurement station, almost all the effects in the mixing layer resulting from the vortex, and the identity of the vortex itself, had subsided.

Bell, W. A.

"SPECTRAL ANALYSIS ALGORITHMS FOR THE LASER VELOCIMETER: A COMPARATIVE STUDY"

AIAA Journal, Vol. 21, No. 5, May 1982, pp. 714-719.

Conventional methods of computing spectra require constant sampling rates and therefore must be modified to accommodate the randomly sampled data from the laser velocimeter. Four approaches that provide estimates of the power spectra from randomly sampled data are evaluated with respect to accuracy and computational speed. Simulated data of varying spectral content are used as input. An estimate of the correlation function that resolves the random time distribution into equidistant time intervals provides the best compromise between computational speed and accuracy for laser velocimeter data.

Bellamy-Knights, P. G.

"AN UNSTEADY TWO-CELL VORTEX SOLUTION OF THE NAVIER-STOKES EQUATIONS"

Journal of Fluid Mechanics, Vol. 41, Part 3, 1970, pp. 673-687.

The steady two-cell viscous vortex solution of Sullivan is extended to yield unsteady two-cell viscous vortex solutions which behave asymptotically as certain analogous unsteady one-cell solutions of Rott.

The radial flux is a parameter of the solution, and the effect of the radial flow on the circumferential velocity, is analyzed. The work suggests an explanation for the eventual dissipation of meteorological flow systems such as tornadoes.

Bellamy-Knights, P. G. and Saci, R.

"VISCOUS VORTEX CORE GENERATION"

Acta Mechanica, Vol. 67, 1987, pp. 121-127.

The unsteady flow of a viscous incompressible fluid between two porous co-axial circular cylinders is analyzed when the outer cylinder is impulsively set into rotation. When there is radial inflow, vorticity is transferred from an unsteady boundary layer initially over the outer cylinder to a steady boundary layer over the inner cylinder.

Bellastrada, C. and Breitsamter, C.

"LARGE TRANSPORT AIRCRAFT WAKE VORTEX AFFECTED BY VORTEX DEVICES"

Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 87, 2004, pp. 1-9.

The results of a wind tunnel investigation on the wake vortex evolution behind a half-model of a four-engine large transport aircraft in high-lift configuration, with and without vortex devices, are presented. The wake is measured by means of advanced hot-wire anemometry up to 5.6 span distances downstream of the model. Results obtained include velocity, vorticity and turbulence intensity fields. The measured data are evaluated in order to establish and test possible wake vortex strength alleviation strategies.

Bellastrada, C. and Breitsamter, C.

"EFFECT OF DIFFERENTIAL FLAP SETTINGS ON THE WAKE VORTEX EVOLUTION OF LARGE TRANSPORT AIRCRAFT"

Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 92, 2006, pp. 25-32.

Wind tunnel investigations have been performed to study the effect of different span loadings, obtained by means of differential flap settings, on the structure of the wake vortex behind a half-model of a four-engine large transport aircraft. Advanced hot-wire anemometry technique has been used to measure the wake vortex velocities at five cross stations up to 4.5 span distances downstream of the model. Results obtained are analyzed to identify possible benefits in terms of alleviation of the wake vortex hazard.

Bellastrada, C., Breitsamter, C. and Laschka, B.

"HOT-WIRE MEASUREMENTS OF WAKE VORTICES SHED FROM A TRANSPORT AIRCRAFT IN LANDING CONFIGURATION"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

The task of the Institute for Fluid Mechanics (FLM - Lehrstuhl fuer Fluidmechanik) of TU Muenchen is the investigation of the turbulent flow field of wake vortex originating from a four-engine large transport aircraft (LTA-E4) half-model in landing configuration. Using advanced hot-wire measurement technique the three velocity components of the wake flow field are measured over rectangular planes located at six different stations downstream of the model, up to six wing span distances downstream of the wing. Typical averaged quantities show the development of the wake: the initial vortex sheet at $x=0.37$, the merging of the vortices coming from the outboard flap edge and from the outboard nacelle giving the main vortical structure, which acts as the roll-up center of the whole wake. The vortices coming from the inboard nacelle, the wing-fuselage junction and from the horizontal stabilizer decrease very soon in strength. At $x=5.56$ the two most important vortical structures, the wing-tip vortex and the outboard flap vortex, merge together into a single strong vortex. Turbulence intensities and Reynolds stresses components reach their maximum peaks inside the core region of the vortices indicating the high stress level which the flow undergoes in the vortex core regions.

Belotserkovskii, Al. S. and Ginevskii, A. S.

"NUMERICAL SIMULATION OF A FAR VORTEX WAKE FOR AN AIRCRAFT IN THE TAKEOFF AND LANDING REGIMES"

Doklady Physics, Vol. 46, No. 10, 2001, pp. 747-750

The results of numerically simulating the two-dimensional problem on the interaction of a vortex pair with a screen make it possible to describe basic features of this interaction. We imply the flow separation from the screen, the interaction of the primary and secondary vorticity, and the creation of the loop-shaped trajectory for the motion of primary vortices. We consider the quasi-three-dimensional schematization of the flow. In other words, we analyze the behavior of the vortex system in a number of cross sections corresponding to different time moments. We list characteristic features of this method used for numerically simulating the airplane vortex system near the Earth.

Belotserkovskii, O. M., Belotserkovskaya, M. S., Denisenko, V. V., Eriklintsev, I. V., Kozlov, S. A., Oparina, E. I., Troshkin, O. V. and Fortova, S. V.

"ON THE DEVELOPMENT OF A WAKE VORTEX IN INVISCID FLOW"

Computational Mathematics and Mathematical Physics, Vol. 54, No. 1, 2014, pp. 172-176.

The evolution of an initial perturbation in an axisymmetric subsonic normal inviscid gas flow through a pipe is directly simulated. The basic (unperturbed) flow has a zero radial velocity component, while its axial velocity component (along the axis of symmetry) increases or decreases linearly with the radius. The perturbation is specified as a swirl (rotation about the axis) with a positive or negative

velocity vanishing on the central axis and the lateral surface. Irrespective of its direction, the swirl gives rise to a steady-state vortex carried by the flow. Its shape is spherical (contiguous to the rotation axis) or circular (sliding along the impermeable lateral surface).

Belotserkovsky, A.

"MATHEMATICAL MODEL OF FAR WAKES: TESTING AND SENSITIVITY"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 59-61

The lecture is devoted to computer integration of the near wake database (array of aerodynamic derivatives of free vortex circulations at aircraft trailing edges) and the other data with the mathematical model (MM) of far wakes. Wake evolution past aircraft is considered. The influence of the ground is included by the mirror vortices (vertical velocities are zero) and the ground boundary layer (horizontal velocities are zero). We consider generation of additional free vortices due to the boundary layer separation, as well as viscous effects yielding vortex diffusion. The numerical integration of differential equations is performed according to the Adams-Bashforth scheme. The lecture contains analysis of the test results of the far wake MM based on flight experiments (Idaho Falls and Memphis, about 150 flights). The test results demonstrate acceptable accuracy of the MM and a possibility of its use in the VFS.

Belotserkovsky, A.

"EVALUATION OF DANGER AREAS AND VFS PERFORMANCE"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 55-57

The VFS must predict vortex conditions at airports and eliminate the possibility of danger situations that could yield accidents due to the action of wake vortices. To this end we determine danger areas behind aircraft near vortex cores. It is necessary to calculate the danger areas for different distances from the aircraft. The method of efficient evaluation of aerodynamic disturbances acting on aircraft in wake vortices of a leader is described. The criterion of safety is chosen. The next step is calculation of a database of danger areas for different pairs of leader-follower. For evaluation of the VFS performance we consider a standard glidepath. A control section is a rectangle along the glidepath where the presence of any of the two vortex cores makes it impossible for the follower to enter it. The dimensions are determined by the accuracy in maintaining the glidepath by the pilot of the leader, by the dimensions of the danger areas for the corresponding pair, and errors in prediction of the leader far wake by the far wake model. The time separation acceptable for the follower is determined by the time period when all sections will be free of the wake vortices. The main factor which determines this time period is the wind velocity.

Belotserkovsky, A., Baranov, N. and Kanevsky, M.

"NEW PRINCIPLES IN THE AREA OF WAKE VORTEX SAFETY FOR AIR TRAFFIC CONTROL"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

Serious efforts being made recently for wake vortex safety all over the world require, in our opinion, thorough investigation of the ways of design, construction and implementation of air traffic control systems intended to alleviate wake vortex risks, increase airport capacity, and lighten the work of pilots. The main problem is that the increase in the airport capacity (using the reduced separations between aircraft) results in the inevitable decrease of the wake vortex safety. The only way to overcome this trouble is to provide the pilots with visual information on possible locations of dangerous wake vortices invisible to the eye. In view of the fact that instrumental methods of wake vortex detection are not valid, we suggest to use the numerical methods adapted to this aim. The airborne system to prevent the aircraft entering into wake vortices of a vortex generator (typically, another aircraft - the leader) consists of: the unit tracking parameters of the generator and the aircraft provided with the system (below - the aircraft); the unit calculating the wake vortices of the generator; the unit simulating the control plane situated at some distance ahead of the aircraft perpendicular to the aircraft velocity vector; the unit indicating a dangerous situation when the wake vortices lie within the prescribed zone (the zone of the aircraft possible positions at the time of the flight through the control plane) in the control plane; and some other auxiliary units. The system functions as follows: When the generator wake vortices are away from the prescribed zone, the vortices are not visible on the indicator screen. As soon as they are close enough to the zone, they become visible and the sound alarm notifies the pilot about the situation. Then the pilot decides which actions could prevent the vortex entering into the zone.

Belotserkovsky, A., Baranov, N., Kanevsky, M., Pasekunov, I. and Morozov, V.

"SIMULATION OF AMBIENT TURBULENCE EFFECTS ON CAPACITY OF A SINGLE RUNWAY AIRPORT EQUIPPED WITH THE VORTEX FORECASTING SYSTEM"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

A model of a single runway airport equipped with the Vortex Forecasting System (VFS) is developed. According to this model, all aircraft flying to the terminal area are aligned in the approach sequence on the first-come, first served basis. It is supposed that all the aircraft in the terminal area have the same flight speed. The aircraft are divided into 3 classes: heavy, large, and light aircraft. Each of the classes has its own landing speed. The safe separations in the approach sequence depend on the classes of aircraft in the leader-follower pair and evaluated through calculation of the wake vortex release times for 5 windows located along the glidepath (these windows are like the corresponding windows in the AVOSS). The aircraft flight through a window is safe if the window is free of the danger areas related to the leader wake vortices (including the case when the vortices are inside the window but very weak). The danger criterion for evaluation of danger areas is the following: the rolling moment due to the

wake vortices is more than one half the available aileron rolling moment of the follower or, otherwise, the follower maximum angle of roll is more than 15 degrees. The position and intensity of the wake vortices are calculated using the VFS algorithms (taking account of in-ground effects). The calculation errors are included into the model through the corresponding increase of the danger areas. The airport is simulated as a queuing system. The wind values are random with the known probability distribution. The length of the aircraft sequence in the airport terminal area is limited by the terminal area dimension, so some arriving aircraft could not be included into the sequence under unfavorable conditions and should wait some time (the service failure). The calculation results for the capacity gains as functions of the ambient turbulence index are submitted. The results demonstrate losses in airport capacity gains when the accuracy of ambient turbulence forecasting is low. The results could support the elaboration of requirements for the turbulence forecasting accuracy at different levels of the system performance.

Belotserkovsky, S. M.

"COMPUTERIZED STUDY OF VORTEX AEROHYDRODYNAMICS OF AIRCRAFT AND HELICOPTERS"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 20-1 - 20-33

The main research in the USSR is conducted by Central Aerohydrodynamics Institute (TsAGI) (calculations, computer simulations, wind-tunnel tests) and by Flight Research Institute (LII) (in-flight experiments) with participation of some other institutions. The principal objective is to ensure flight safety and to make better use of the potential of aircraft, helicopters, and airfields. To meet these demands it is necessary to study: wake vortices behind aircraft and helicopters; their effects on other aircraft and bodies; and dynamics of disturbed motion of the bodies. The most operative and cheap approach was selected, i.e., systematic computer simulation with selective experimental wind-tunnel and in-flight tests.

Belotserkovsky, S. M.

"STRUCTURE AND PRINCIPLES OF THE VFS FUNCTIONING"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 51-54

The solution to the problem of forecasting vortex danger at airports is addressed through the use of up-to-date computer technologies, modern methods of data acquisition on meteorological conditions surrounding an airport, and exhibition of the vortex danger prediction for flight control services. This lecture summarizes the 4-year activity of SABIGO together with Canadian researchers.

Belotserkovsky, S. M.

"COMPUTER VORTEX FORECAST SYSTEM"

TP-13373E, March 1999, Science-Engineering Centre SABIGO Ltd., Moscow, Russia.

This report describes phase 4 wake vortex prediction investigations conducted by SABIGO from April 1997 to March 1998. The report presents an enhancement of the far wake model of the vortex forecast system (VFS) that incorporates the ground boundary layer. Also provided are the results of a VFS evaluation using aircraft wake data collected at the Memphis International Airport in December 1994 and August 1995. The report also covers the following: extension of the near wake database to include more aircraft types; investigation of danger areas considering ground effects; and development of an approach to evaluate VFS performance during aircraft takeoff field trials.

Belyaev, I. V. and Kopiev, V. F.

"ON SOUND SCATTERING BY A RANKINE VORTEX"

AIAA Paper No. 2007-3421, Rome, Italy, May 2006

In the paper, the well-known problem of sound scattering by a Rankine vortex is considered. Despite almost semi-centennial history of the problem, it has not yet been solved satisfactorily. The main difficulty is the fact that the slow decrease of the mean velocity at the infinity hinders the correct formulation of the problem. It results in arising of multiple solutions, each of which pretends to be correct, including the solutions with singularities behind the vortex. A new formulation of the problem is proposed that allows to regularize the problem and to find the solution corresponding to the physical essence of the problem. It is shown that instead of plane wave condition it is necessary to pose the condition of the point source far from the vortex. The analysis made in the paper clarifies the cause of the multiplicity of answers and allows to compare the existing approaches. In the new formulation, the exact solution of the problem of non-resonant sound scattering by the Rankine vortex in the weakly compressible approximation is found. The different results for the resonant scattering are analyzed and the result unifying the previous ones is found. This approach demonstrates the benefit of partial harmonic expansion method in comparison with the Born approximation approach in Lighthill's equation due to unified consideration of non-resonance and resonance scattering.

Ben-Dov, G., Levinski, V. and Cohen, J.

"OPTIMAL DISTURBANCES IN SWIRLING FLOWS"

AIAA Journal, Vol. 42, No. 9, Sept. 2004, pp. 1841-1848

The mechanism of optimal disturbances, which are composed of growing and decaying modes, in swirling flows (with an axial velocity component) is explored. Two characterizing cases are considered; stationary disturbances in rotating pipe flow and temporal disturbances in a trailing vortex. It is found that in both cases the optimal transient growth amplification in short times or distances is much larger than the known exponential mode amplification. Unlike the flow in a nonrotating pipe, in which the amplification is based on the existence of a least stable pair of modes and the cancellation of their associated initial axial velocity components, when a rotation is added to the flow the optimal amplification mechanism is based on the cancellation, at the initial state, of the most unstable mode

velocity components by many decaying modes. For the trailing vortex, the transient growth mechanism seems to be based on the contribution of the continuous spectrum, and the optimal transient growth is not significantly affected by the existence of swirl in the flow.

Bengin, A.

"THREE-DIMENSIONAL ROTOR FLOW CALCULATION"

FME Transactions, Vol. 33, 2005, pp. 33-39.

This paper presents the numerical model developed for rotor blade aerodynamics loads calculations. The model is unsteady and fully three-dimensional. Helicopter blade is assumed to be rigid, and its motion during rotation is modeled in the manner that rotor presents a model of rotor of helicopter Aerospatiale SA 341 'Gazelle' (the blade is attached to the hub by flap, pitch and pseudo lead-lag hinges). Flow field around the blade is observed in succession of several azimuth locations. Flow field around helicopter rotor is modeled as fully three-dimensional, unsteady and potential. Blade aerodynamics is modeled using a lifting surface model. Rotor wake is generated from the straight elements of constant vorticity, released from the trailing edge, at fixed azimuth angles. These vortices represent both trailed and shed wake components, and are allowed to freely convect along local velocity vectors. Wake is modeled as free one, and its shape at certain moment can be calculated from simple kinematics laws applied on collocation points of the wake. Wake distortion is calculated only in the rotor near-field, i.e. in finite number of rotor revolutions. Vortex elements are modeled with vortex core. The radius of the vortex core is assumed independent of time, and it depends on circulation gradient at the point of vortex element released from the blade.

Bengin, A. and Jeremic, S.

"THREE-DIMENSIONAL ROTOR FLOW CALCULATION"

ICAS 1998, Sept. 1998, Melbourne, Australia.

This paper presents the numerical model developed for rotor blade aerodynamics loads calculation. The model is unsteady and fully three-dimensional. Helicopter blade is assumed to be rigid, and its motion during rotation is modeled in the manner that rotor presents a model of rotor of helicopter Aerospatiale SA 341 'Gazelle' (the blade is attached to the hub by flap, pitch and pseudo lead-lag hinges). Flow field around the blade is observed in succession of several azimuth locations. Flow field around helicopter rotor is modeled as fully three-dimensional, unsteady and potential. Blade aerodynamics is modeled using a lifting surface model. Rotor wake is generated from the straight elements of constant vorticity, released from the trailing edge, at fixed azimuth angles. These vortices represent both trailed and shed wake components, and are allowed to freely convect along local velocity vectors. Wake is modeled as free one, and its shape at certain moment can be calculated from simple kinematics laws applied on collocation points of the wake. Wake distortion is calculated only in the rotor near-field, i.e. in finite number of rotor revolutions. Vortex elements are modeled with vortex

core. The radius of the vortex core is assumed independent of time, and it depends on circulation gradient at the point of vortex element released from the blade.

Beninati, M. L. and Marshall, J. S.

"AN EXPERIMENTAL STUDY OF THE EFFECT OF FREE-STREAM TURBULENCE ON A TRAILING VORTEX"

Experiments in Fluids, Vol. 38, 2005, pp. 244-257.

A study of turbulence evolution and spectra within and just outside the core of a trailing vortex is performed. The vortex is generated by a vortex generator consisting of four blades positioned orthogonally to each other with the same angle of attack and placed in a low-speed wind tunnel. A grid is placed upstream of the vortex generator to produce free-stream turbulence, which wraps around and interacts with the columnar vortex. Instantaneous measurements of the three velocity components are obtained using a miniature four-sensor hot-wire probe. The study focuses on the distribution of turbulence energy and Reynolds stress among the different spectral components of the flow at different positions across the vortex core and different axial positions along the tunnel. The effect of background grid turbulence on the spectral energy distribution of the vortex is examined in comparison to the vortex alone.

Beninati, M.-L., McErlean, M., Krane, M. and Fontaine, A.

"EFFECT OF A GROUND PLANE ON A TURBULENT VORTEX RING TRAJECTORY"

63rd Annual Meeting of the APS Division of Fluid Dynamics, November 2010, Long Beach, CA.

Experiments were conducted to assess how a turbulent ($Re=20000$) vortex ring's trajectory is affected by a ground plane parallel to its initial trajectory. This study, part of a larger effort in vortex-particle interaction, aims to characterize the vortex ring flow disturbance that interacts with a particle. Vortex ring motion was characterized for four distances between the initial vortex ring axis and the ground plane. Characterization included vortex centroid motion and diameter from high-speed video, vortex ring circulation from DPIV, and the wall pressure disturbance time traces. It was observed that in all cases the vortex ring trajectory is deflected toward the plane, ending in a collision. As plate height is decreased, the collision occurs closer to the ring generator, the wall pressure is also more intense, and the symmetry of the ring is affected more strongly.

Benjamin, S. G., Schwartz, B. E. and Cole, R. E.

"ACCURACY OF ACARS WIND AND TEMPERATURE OBSERVATIONS DETERMINED BY COLLOCATION"

Weather and Forecasting, Vol. 14, No. 6, 1999, pp. 1032-1038.

A collocation study of meteorological reports from commercial aircraft relayed through the Aircraft Communications, Addressing, and Reporting System (ACARS) has been performed to estimate standard deviations of observation errors for wind and temperature. ACARS observations were collected over an

area in the western and central United States for a 13-month period, and this dataset was examined for pairs of reports within small spatial (less than or equal to 10 km) and temporal (less than or equal to 10 min) windows. The results showed an observation error of a single horizontal component of wind of 1.1 m/s and 0.5 K for temperature above the boundary layer. Within the boundary layer, the rms difference of wind and temperature between aircraft was larger, presumably due to larger small-scale variations in the atmosphere and, in the case of wind, from aircraft maneuvers. These observation error estimates are valuable for use in data assimilation and for determination of forecast error from ACARS observation-minus-forecast differences. By comparing standard deviations at different levels, estimates of mesoscale variability at a 10-km scale in the lower atmosphere were also calculated. These values (rms vector error of 1.8 m/s for wind, rms error of 0.5 K for temperature) can be interpreted as estimates of the 10-km lower-tropospheric error of representativeness, also useful for data assimilation.

Benjamin, T. B.

"THEORY OF THE VORTEX BREAKDOWN PHENOMENON"

J. Fluid Mech., Vol. 14, June 1962, pp. 38-44

The phenomenon examined is the abrupt structural change which can occur at some station along the axis of a swirling flow, notably the leading-edge vortex formed above a delta wing at incidence. Contrary to previous attempts at an explanation, the belief demonstrated herein is that vortex breakdown is not a manifestation of instability or of any other effect indicated by study of infinitesimal disturbances alone. It is instead a finite transition between two dynamically conjugate states of axisymmetric flow, analogous to the hydraulic jump in open-channel flow. A set of properties essential to such a transition, corresponding to a set shown to provide a complete explanation for the hydraulic jump, is demonstrated with wide generality for axisymmetric vortex flows; and the interpretation covers both the case of mild transitions, where an undular structure is developed without the need arising for significant energy dissipation, and the case of strong ones where a region of vigorous turbulence is generated.

Benjamin, T. B.

"SIGNIFICANCE OF THE VORTEX BREAKDOWN PHENOMENON"

J. Basic Engineering, Vol. 87, June 1965, pp. 518-522

The essential points in the author's published theory of the vortex breakdown phenomenon are summarized, and their implications regarding longitudinal vortex flows in general are reviewed. It is proposed that the physical principles serve to rationalize a wide variety of possible behavior in swirling flows.

Benjamin, T. B.

"SOME DEVELOPMENTS IN THE THEORY OF VORTEX BREAKDOWN"

J. Fluid Mech., Vol. 28, Part 1, April 1967, pp. 65-84

This analysis consolidates the ideas of the 'conjugate-flow' theory, which proposes that vortex breakdown is fundamentally a transition from a uniform state of swirling flow to one featuring stationary waves of finite amplitude. The original flow is assumed to be supercritical (i.e., incapable of bearing infinitesimal stationary waves), and the mechanism of the transition is explained based on physical principles that are well established in relation to the analogous supercritical flow phenomenon of the hydraulic jump or bore.

Benkenida, A., Bohbot, J. and Jouhaud, J. C.

"PATCHED GRID AND ADAPTIVE MESH REFINEMENT STRATEGIES FOR THE CALCULATION OF THE TRANSPORT OF VORTICES"

International Journal for Numerical Methods in Fluids, Vol. 40, Issue 7, pp. 855-873

This paper presented two techniques allowing local grid refinement to calculate the transport of vortices, one is the patched grid (PG) method which allows non-coincident interfaces between blocks. Treatment of the non-coincident interfaces is given in detail. The second one is the adaptive mesh refinement (AMR) method which has been developed to create embedded sub-grids. The efficiency of these two methods is demonstrated by some validating tests. Then the PG and AMR strategies are applied in the computation of the transport of vortices. We start with a simple vortex flow in a cubic box. Then, the flowfield around a complex aircraft configuration is calculated using the two refinement techniques. Results are compared with a fine, referenced grid calculation.

Benkenida, A., Bohbot, J. and Jouhaud, J.-C.

"PATCHED GRID AND ADAPTIVE MESH REFINEMENT STRATEGIES FOR WAKE VORTEX TRANSPORT CALCULATION"

AIAA Paper No. 2001-2416, Anaheim, CA, June 2001

Applying mesh refinement strategies to the study of wake vortices is the principal subject of this study. We simulate the inviscid flow around a generic aircraft model using Patched grid and Adaptive Mesh Refinement techniques. The analysis of numerical results shows that the application of these strategies to wake vortices problems is promising, especially when we study complex cases in which it is necessary to use very fine grids and consequently enormous CPU times.

Benkenida, A., Jonville, G. and Darracq, D.

"NUMERICAL STUDY OF WAKE VORTICES OF A GENERIC AIRCRAFT MODEL"

AIAA Paper No. 2001-2428, Anaheim, CA, June 2001

This paper presents the numerical simulation of the wake vortices induced by the high lift system of an aircraft model up to the extended near field (6.5 and 13 wingspans) by the means of high-quality meshes and high-order schemes. Numerical simulations are done by the NSMB code which solves the three-dimensional Navier-Stokes equations (Euler equations here) on multi-block structured grids. The most important point discussed in this paper is the effect of the angle of attack on the behavior of wake vortices and their mutual interaction.

Benner, M. S., Dunham, R. E. and Verstynen, H. A.

"EXPLORATORY STUDY OF C-130 AND C-47 AIRCRAFT TRAILING VORTICES IN GROUND EFFECT"

LWP-1040, March 1972, NASA Langley Research Center, Hampton, VA

In the development and checkout of an instrumented tower which is to be used to measure the velocity characteristics of aircraft trailing vortices, some measurements were made of trailing vortices shed by a NASA C-47 airplane and an Air Force C-130 airplane. The report describes the instrumentation and testing technique used and presents some preliminary results on the vortex characteristics of the C-47 and C-130 aircraft shed in close proximity to the ground.

Bennett, D. J., Covert, E. E. and Oliver, T.

"THE WING GRID: A NEW APPROACH TO REDUCING INDUCED DRAG"

Final Report, 16.622, December 2001, MIT, Cambridge, MA.

A new design of wing tip, called a wing grid, has been shown to provide a dramatic reduction in the induced drag a wing produces. This experimental project was performed to quantify that reduction and to better understand the wing grid effect. A model wing including three modular wing tips two different designs of wing grids and a control tip were constructed and tested at various wind speed and angles of attack in a wind tunnel. The performance of the wing grids relative to the control and to each other was investigated. The experiment showed that at low speeds, the wing grid does not reduce drag, but suggested that it might do so at higher speeds.

Bennett, W. J.

"ANALYTICAL DETERMINATION OF THE VELOCITY FIELDS IN THE WAKES OF SPECIFIED AIRCRAFT"

FAA-RD-64-55, May 1964, Boeing Co., Renton, WA

This report documents a study for the prediction of the velocity fields in the wakes of fixed-wing and rotary-wing aircraft. Thirty-three aircraft currently operating within the Air Traffic Control system are analyzed. Numerical data are presented for eleven of the aircraft, defining their respective wake velocity fields. A discussion of the assumptions and limitations of the analytical models used is included along with a discussion of possible correlation of the calculated values with test results.

Bennett, W. J.

"STATE-OF-THE-ART SURVEY FOR MINIMUM APPROACH, LANDING, AND TAKE-OFF INTERVALS AS DICTATED BY WAKES, VORTICES, AND WEATHER PHENOMENA"

FAA-RD-64-4, January 1964, Boeing Co., Renton, W.

This report is a study of the generation and decay of the wake behind an aircraft, both in free air and ground effect, and its effect on following aircraft. An analysis is presented for both fixed and rotary-wing aircraft which defines the wake movement with time and the wake-induced velocities. The influence of atmospheric parameters such as wind, temperature, and turbulence is discussed as it applies to the generation and decay of the wake.

Benton, S. I.

"CAPITALIZING ON CONVECTIVE INSTABILITIES IN A STREAMWISE VORTEX-WALL INTERACTION"

PhD Thesis, 2015, The Ohio State University, Columbus, OH.

Secondary flows in turbomachinery and similar engineering applications are often dominated by a single streamwise vortex structure. Investigations into the control of these flows using periodic forcing have shown a discrete range of forcing frequency where the vortex is particularly receptive. Forcing in this frequency range results in increased movement of the vortex and decreased total pressure losses. Based on the hypothesis that this occurs due to a linear instability associated with the Crow instability, a fundamental study of instabilities in streamwise vortex-wall interactions is performed. In the first part of this study a three-dimensional vortex-wall interaction is computed and analyzed for the presence of convective instabilities. It is shown that the Crow instability and a range of elliptic instabilities exist in a similar form as to what has been studied in counter-rotating vortex pairs. The Crow instability is particularly affected by the presence of a solid no-slip wall. Differences in the amplification rate, oscillation angle, Reynolds number sensitivity, and transient growth are each discussed. The spatial development of the vortex-wall interaction is shown to have a further stabilizing effect on the Crow instability due to a 'lift-off' behavior. Despite these discoveries, it is still shown that amplitude growth on the order of 20 percent is possible and transient growth mechanisms might result in an order-of-magnitude of further growth if properly initiated. With these results in mind, an experiment is developed to isolate the streamwise vortex-wall interaction. Using a vortex generating wing section and a suspended splitter plate, a stable interaction is created that agrees favorably in structure to the three-dimensional computations. A small synthetic jet actuator is mounted on the splitter plate below the vortex. Phase-locked stereo-PIV velocity data and surface pressure taps both show spatial amplification of the disturbance in a frequency range which agrees well with the prediction for the Crow instability. An analysis of the vortex response shows a primarily horizontal oscillation of the vortex column which strongly interacts with the secondary vortex structure that develops in the boundary layer.

Benton, S. I. and Bons, J. P.

"RESPONSE OF A STREAMWISE VORTEX-WALL INTERACTION TO UNSTEADY FORCING"

AIAA Paper 2016-1605, January 2016, San Diego, CA.

Streamwise vortices exist in several engineering flows in both external and internal aerodynamics, often with undesirable effects. An experimental investigation of a streamwise vortex-wall interaction is performed using a vortex generating wing section and a suspended splitter plate. The unsteady development of the interaction is documented using surface pressure taps and stereo particle image velocimetry. A synthetic jet actuator is implemented below the vortex and the response of the vortex to unsteady forcing is evaluated with a focus on spatial amplification through convective instabilities. At low forcing frequencies large displacement of the vortex is recorded, but with almost no spatial amplification. This behavior is expected to be linked to transient growth mechanisms. Within a specific frequency range, it is shown that spatial amplification of the vortex displacement occurs. This mechanism is related to the Crow instability and has recently been investigated using computational linear stability theory. The results here are in qualitative agreement with those studies. The vortex-wall interaction generates a secondary vortex structure which rolls-up from the boundary layer. This feature is involved in the dynamics of the instability and its behavior is described.

Bera, R. K.

"WING TIP VORTICES OF CYCLONIC PROPORTIONS"

Current Science, Vol. 64, No. 3, February 1993, pp. 138-139

The wing tip trailing vortices that are continuously shed by jumbo jets constitute a hazard to following aircraft if there is not enough lag time allowed between the aircraft. The hazard exists because of the sheer size of these vortices, and the high swirl velocities, which are directly related to vortex strength, contained in them. As an example, swirl velocities on the order of 18.3 m/sec may be found in the vortices shed by a C5-A Galaxy one and a half miles astern, or 30 sec. after the aircraft's passage. The type of hazards include: an aircraft experiencing imposed rolling moments upon penetrating the core of a vortex; loss in rate of climb or an increase in the rate of descent of an aircraft subject to the downwash; and the imposition of structural loads for the case of a penetrating aircraft approaching perpendicular to the vortex system. The use of a crossed blade turbine fixed immediately behind the wing tip, and fences placed near the wing tip above and below the wing, producing a swirl counter to vortex swirl has shown some promise in alleviating this danger. In addition, predominantly aerodynamical solutions to this problem have been proposed. One attempt is to alter the wing spanwise lift distribution by deflected flaps to produce centers of high shed vorticity, so that the wing wake attempts to roll up into several vortex cores, producing weaker individual vortices compared to the present tip vortices, and vortices whose mutual interaction will cause the vortices to destroy themselves in a Crow type instability or by vortex bursting. In the second approach, aerodynamic control surfaces are to be programmed to automatically generate an unsteady pressure distribution on the wing while maintaining constant lift to produce an unsteady wake. Attention is also given to

experimental data regarding aircraft wake behavior, considering the development of vortical and viscous wakes, and characteristic flow regions.

Bera, R. K.

"ACCURATE METHOD FOR CALCULATING INITIAL DEVELOPMENT OF VORTEX SHEETS"

J. Aircraft, Vol. 27, No. 10, October 1990, pp. 910-912

A fast and accurate numerical method for calculating the early evolutionary stages of an initially planar, finite-span vortex sheet has been found. The method may be used to determine wing downwash behind a wing, e.g., in the vicinity of the tail plane.

Bera, R. K.

"CALCULATION OF INITIAL VORTEX ROLL-UP IN AIRCRAFT WAKES"

Journal of Aircraft, Vol. 13, No. 1, January 1976, pp. 58-59

The intention of this note is to rederive the results of Yates by using a Fourier sine series for the lift distribution instead of the Chebyshev polynomials he has used, and to complete the analysis by also considering nonsymmetric flight conditions. These results may be used as the first step in the use of the extended Betz theory for rollup calculations.

Beran, D. W.

"REMOTE SENSING WIND AND WIND SHEAR SYSTEM"

FAA-RD-74-3, January 1974, NOAA Wave Propagation Laboratory, Boulder, CO.

The background for, and developmental history of acoustic Doppler is followed by a detailed study of winds that effect landing operations. A climatology of critical boundary layer wind shear and a study of optimum averaging times for reported winds show that the occurrence of severe wind shear is regional and not to be expected more than a small percentage of the time. Analysis of several ground based remote wind sensing devices suggests that the acoustic Doppler system is presently optimum. Weaknesses in any given device may, however, dictate that a joint sensor approach must be used to insure continual real time operation. The selection of an optimum configuration and details of the hardware used during experimental tests at Stapleton International Airport are discussed. Calibration of the Acoustic Doppler Wind System was accomplished by comparison with winds taken by anemometers suspended beneath balloons, tower mounted anemometers and slow ascent radiosondes. Agreement with all of these wind measurements was very good. Results from the operational tests at Stapleton indicate the Acoustic Doppler System can perform in the high noise environment of an airport. The effect of the high noise in terms of percentage of lost record has not yet been determined.

Beran, D. W.

"ACOUSTICS: A NEW APPROACH FOR MONITORING THE ENVIRONMENT NEAR AIRPORTS"

Journal of Aircraft, Vol. 8, No. 11, November 1971, pp. 934-936

The note describes a relatively new device, an acoustic echo sounder, which has the potential to not only indicate the presence or absence of wake vortices, but to act as a continuous monitor of other important meteorological parameters (wind, wind shear, and thermally generated turbulence). A fixed, vertically pointing antenna, in conjunction with two orthogonally positioned scanning antennas could provide a continual real time record of the inversion height, the turbulent intensity, an indication of the presence of wing tip vortices, and the vertical profile of the total wind vector.

Beran, D. W.

"ACOUSTIC RADAR DETECTION TECHNIQUES"

FAA Symposium on Turbulence, 1971, Federal Aviation Administration, Washington, DC, p. 27

Acoustic radar or echo sounding has the potential of providing a solution to both the wake vortex and low-level wind shear monitoring problems, at a cost which is realistic in terms of equipping most large airports with an operational system. Such a system would be based on the demonstrated ability to make Doppler wind measurements with an acoustic sounder (for monitoring strong shear layers) and the amplitude and phase scintillation of an acoustic wave when it is transmitted through a turbulent medium (for detecting wake vortices).

Berenger, T., Faier, D., Maresca, C. and Berton, E.

"EXPERIMENTAL AND NUMERICAL INVESTIGATION OF ROTOR AERODYNAMICS IN FORWARD FLIGHT"

Journal of Aircraft, Vol. 34, No. 3, May-June 1997, pp. 394-399.

This paper concerns an experimental and numerical investigation of the aerodynamic field of a model rotor in forward flight. The study emphasizes the characterization of the flow field in the immediate vicinity of the blade and in its near wake. The analysis of the blade aerodynamics is supported by measurements performed on the overall air loads, the three-dimensional velocity field around the blade and in the wake (determined by means of laser Doppler anemometry measurements), and the geometry of the tip vortex path. The corresponding data results allow the correlation of typical velocity profiles to the vortex characteristics parameters. From the computational approach, the prediction efficiency of a prescribed wake analysis code and its improvement are checked by direct comparisons with experiments performed either on the tip vortex path, or on the three-dimensional velocity field and the circulation distribution along the blade span.

Berens, M.

"POTENTIAL OF MULTI-WINGLET SYSTEMS TO IMPROVE AIRCRAFT PERFORMANCE"

Ph.D. Thesis, Technical University of Berlin, Berlin, Germany, March 2008

The potential of multi-winglet configurations to increase aircraft performance is the subject of the present thesis. A multidisciplinary tool, termed VLM++, has been developed based on an implementation of the 3D vortex lattice method. Apart from consideration of profile and interference drag, the method also considers effects that need to be regarded particularly in the case of multi-winglet configurations. The effect of mutual interference among the winglets on the individual surfaces maximum load abilities is considered, producing values which normally differ from those of the basic airfoil sections. Another module permits to explicitly model the nonlinear lift characteristics based on generalized lift polars. A comparison of the numerical results with published low speed measurement data of multi-winglet configurations having symmetrical NACA 0015 airfoil sections proves that the extended analysis model correctly predicts the lift and drag behavior even in the case of partly separated flow. The computational model correctly identifies the root sections of the foremost winglets as the locations where the flow separations first occur when the angle of attack is increased.

Beresh, S. J., Henfling, J. F. and Spillers, R. W.

"PLANAR VELOCIMETRY OF A FIN TRAILING VORTEX IN SUBSONIC COMPRESSIBLE FLOW"

AIAA Paper 2008-4179, June 2008, Seattle, WA.

A sub-scale experiment has been conducted to study the trailing vortex shed from a tapered fin installed on a wind tunnel wall to represent missile configurations. Stereoscopic particle image velocimetry measurements have been acquired in the near-field for several locations downstream of the fin tip and at different fin angles of attack. The vortex's tangential velocity is found to decay with downstream distance while its radius increases, but the vortex core circulation remains constant. Circulation and tangential velocity rise greatly for increased fin angle of attack, but the radius is approximately constant or slightly decreasing. The vortex axial velocity is always a deficit, whose magnitude diminishes with downstream distance and smaller angle of attack. No variation with Mach number can be discerned in the normalized velocity data. Vortex roll-up is observed to be largely complete by about four root chord lengths downstream of the fin trailing edge. Prior to this point, the vortex is asymmetric in the tangential velocity but the core radius stays nearly constant. Vortical rotation draws low-speed turbulent fluid from the wind tunnel wall boundary layer into the vortex core, which appears to hasten vortex decay and produce a larger axial velocity deficit than might be expected. Self-similarity of the vortex is established even while it is still rolling up. Attempts to normalize vortex properties by the fin's lift coefficient proved unsuccessful.

Beresh, S. J., Henfling, J. F. and Spillers, R. W.

"MEANDER OF A FIN TRAILING VORTEX AND THE ORIGIN OF ITS TURBULENCE"

Experimental Fluids, Vol. 49, 2010, pp. 599-611.

The low-frequency meander of a trailing vortex shed from a tapered fin installed on a wind tunnel wall has been studied using stereoscopic particle image velocimetry in the near-wake at Mach 0.8. Distributions of the instantaneous vortex position reveal that the meander amplitude increases with downstream distance and decreases with vortex strength, indicating meander is induced external to the vortex. Trends with downstream distance suggest meander begins on the fin surface, prior to vortex shedding. Mean vortex properties are unaltered when considered in the meandering reference frame, apparently because turbulent fluctuations in the vortex shape and strength dominate positional variations. Conversely, a large peak of artificial turbulent kinetic energy is found centered in the vortex core, which almost entirely disappears when corrected for meander, though some turbulence remains near the core radius. Turbulence originating at the wind tunnel wall was shown to contribute to vortex meander by energizing the incoming boundary layer using low-profile vortex generators and observing a substantial increase in the meander amplitude, while greater turbulent kinetic energy penetrates the vortex core. An explanatory mechanism has been hypothesized, in which the vortex initially forms at the apex of the swept leading edge of the fin where it is exposed to turbulent fluctuations within the wind tunnel wall boundary layer, introducing an instability into the incipient vortex core.

Beresh, S. J., Smith, J. A., Henfling, J. F., Grasser, T. W. and Spillers, R. W.

"INTERACTION OF A FIN TRAILING VORTEX WITH A DOWNSTREAM CONTROL SURFACE"

AIAA Paper No. 2008-342, Reno, NV, Jan. 2008

A sub-scale experiment has been constructed using fins mounted on one wall of a transonic wind tunnel to investigate the influence of fin trailing vortices upon downstream control surfaces. Data are collected using a fin balance instrumenting the downstream fin to measure the aerodynamic forces of the interaction, combined with stereoscopic Particle Image Velocimetry to determine vortex properties. The fin balance data show that the response of the downstream fin essentially is shifted from the baseline single-fin data dependent upon the angle of attack of the upstream fin. Freestream Mach number and the spacing between fins have secondary effects. The velocimetry shows that the vortex strength increases markedly with upstream fin angle of attack, though even an uncanted fin generates a noticeable wake. No variation with Mach number can be discerned in the normalized velocity data. Correlations between the force data and the velocimetry suggest that the interaction is fundamentally a result of an angle of attack superposed upon the downstream fin by the vortex shed from the upstream fin tip. The Mach number influence arises from differing vortex lift on the leading edge of the downstream fin even when the impinging vortex is Mach invariant.

Beresh, S. J., Smith, J. A., Henfling, J. F., Grasser, T. W. and Spillers, R. W.

"INTERACTION OF A FIN TRAILING VORTEX WITH A DOWNSTREAM CONTROL SURFACE"

Journal of Spacecraft and Rockets, Vol. 46, No. 2, March-April 2009, pp. 318-328.

A subscale experiment has been constructed using fins mounted on one wall of a transonic wind tunnel to investigate the influence of fin trailing vortices upon downstream control surfaces. Data were collected using a fin balance instrumenting the downstream fin to measure the aerodynamic forces of the interaction, combined with stereoscopic particle image velocimetry to determine vortex properties. The fin balance data show that the response of the downstream fin essentially is shifted from the baseline single-fin data dependent upon the angle of attack of the upstream fin. Freestream Mach number and the spacing between fins have secondary effects. The velocimetry shows the increase in vortex strength with upstream fin angle of attack, but no variation with Mach number can be discerned in the normalized velocity data. Correlations between the force data and the velocimetry indicate that the interaction is fundamentally a result of an angle of attack superposed upon the downstream fin by the vortex shed from the upstream fin tip. The Mach number influence arises from differing vortex lift on the leading edge of the downstream fin even when the impinging vortex is Mach invariant.

Bergdorf, M., Koumoutsakos, P. and Leonard, A.

"DIRECT NUMERICAL SIMULATIONS OF VORTEX RINGS AT REYNOLDS NUMBER OF 7500"

J. Fluid Mech., Vol. 581, 2007, pp. 495-505

We present direct numerical simulations of the turbulent decay of vortex rings with Reynolds Number of 7500. We analyze the vortex dynamics during the nonlinear stage of the instability along with the structure of the vortex wake during the turbulent stage. These simulations enable the quantification of vorticity dynamics and their correlation with structures from dye visualization and the observations of circulation decay that have been reported in related experimental works.

Berger, S. A. and Erlebacher, G.

"VORTEX BREAKDOWN INCIPIENCE: THEORETICAL CONSIDERATIONS"

Phys. Fluids, Vol. 7, No. 5, May 1995, pp. 972-982 (Also ICASE-92-63, November 1992, Inst. for Computer Applications in Science and Engineering, Hampton, VA)

The sensitivity of the onset and the location of vortex breakdowns in concentrated vortex cores, and the pronounced tendency of the breakdowns to migrate upstream have been characteristic observations of experimental investigations; they have also been features of numerical simulations and led to questions about the validity of these simulations. This behavior seems to be inconsistent with the strong time-like axial evolution of the flow, as expressed explicitly, for example, by the quasi-cylindrical approximate equations for this flow. An order-of-magnitude analysis of the equations of motion near breakdown leads to a modified set of governing equations, analysis of which demonstrates that the interplay between radial inertial, pressure, and viscous forces gives an elliptic character to these concentrated swirling flows. Analytical, asymptotic, and numerical solutions of a simplified non-linear equation are presented; these qualitatively exhibit the features of vortex onset and location noted above.

Bergeron, K., Ghoreyshi, M., Jirasek, A. and Lofthouse, A. J.

"SIMULATION OF C-130 H/J TROOP DOORS AND CARGO RAMP FLOW FIELDS"

AIAA Paper 2017-0967, January 2017, Grapevine, TX.

This paper presents the results of a continuing computational effort to understand the flow field characteristics of a C-130 Hercules aircraft configured for personnel airdrop operations. Flight operations with either the troop door or cargo door open lead to vortical structures and unsteady flows which can adversely affect airdrop operations. Open cargo ramp simulation results using the CFD solver Kestrel, developed within the High Performance Computing Modernization Program CREATE-AV program, show vorticity generated behind the open cargo door and with the flaps extended, a relatively strong vortex forms along the fuselage which traverses above the troop door into the upsweep section of the aircraft tail. Open troop door simulations capture large velocity gradients and unsteadiness for configurations with and without actuator disk propeller models and with and without sideslip. Simulations are computed on both converged hybrid meshes on the order of $100 \times 1,000,000$ cells and near-body/cartesian off-body grids, and these results reconfirm that vortex modeling is dependent on mesh refinement.

Bergh, H. and Tijdeman, H.

"THEORETICAL AND EXPERIMENTAL RESULTS FOR THE DYNAMIC RESPONSE OF PRESSURE MEASURING SYSTEMS"

NLR-TR F.238, January 1965, National Aero- and Astronautical Research Institute, Amsterdam, The Netherlands.

For a series-connection of N thin tubes and N volumes a general recursion formula has been derived that relates the sinusoidal pressure disturbance in volume j to the pressure disturbances in the preceding volume $j-1$ and the next volume $j+1$. From this recursion formula the expressions for the complex ratio of the pressure fluctuation of each volume j to the sinusoidal input pressure $p_{sub 0}$ can be derived by successively putting $j = N, N-1, \dots, 2, 1$. For a single pressure measuring system ($N = 1$) and a double pressure measuring system ($N = 2$) these dynamic response formulae are given explicitly. Theoretical results for single pressure measuring systems are presented that demonstrate the influence of the different parameters. As an illustrative example of the double pressure measuring system some calculations have been performed for a system with a discontinuity in tube radius. Comparison of theoretical and experimental results shows that the response characteristics of the pressure measuring systems considered can be predicted theoretically to a high degree of accuracy.

Berk, L. A. and Hallock, J. N.

"PREDICTING NEAR-GROUND VORTEX LIFETIMES USING WEIBULL DENSITY FUNCTIONS"

AIAA Paper No. 2007-1057, Reno, NV, January 2007

To mitigate safety hazards posed by near-ground vortex lateral transport, under instrument flight rules (IFR), parallel runway operations must adopt aircraft spacing standards that often reduce capacity. Once the phenomenon of lateral transport is understood, it is conceivable that, under IFR, new separation standards could restore some runway capacity. In this context, it is of interest to establish the probability that a wake vortex is still surviving in lateral transport time seconds after it began migrating. This paper applies survival data analysis methods to demonstrate how to generate predictions of survival probability that are specific to aircraft type. Modeling assumptions lead to a family of Weibull probability densities, a form that is useful for modeling wind phenomenon.

Berkman, M. E.

"AN INTEGRATED NAVIER-STOKES -- FULL POTENTIAL -- FREE WAKE METHOD FOR ROTOR FLOWS"

PhD Thesis, December 1998, Georgia Institute of Technology, Atlanta, GA.

The strong wake shed from rotary wings interacts with almost all components of the aircraft, and alters the flow field thus causing performance and noise problems. Understanding and modeling the behavior of this wake, and its effect on the aerodynamics and acoustics of helicopters have remained as challenges. This vortex wake and its effect should be accurately accounted for in any technique that aims to predict rotor flow field and performance. In this study, an advanced and efficient computational technique for predicting three-dimensional unsteady viscous flows over isolated helicopter rotors in hover and in forward flight is developed. In this hybrid technique, the advantages of various existing methods have been combined to accurately and efficiently study rotor flows with a single numerical method. The flow field is viewed in three parts: (i) an inner zone surrounding each blade where the wake and viscous effects are numerically captured, (ii) an outer zone away from the blades where wake is modeled, and (iii) a Lagrangian wake which induces wake effects in the outer zone. This technique was coded in a flow solver and compared with experimental data for hovering and advancing rotors including a two-bladed rotor, the UH-60A rotor and a tapered tip rotor. Detailed surface pressure, integrated thrust and torque, sectional thrust, and tip vortex position predictions compared favorably against experimental data. Results indicated that the hybrid solver provided accurate flow details and performance information typically in one-half to one-eighth cost of complete Navier-Stokes methods.

Bernstein, S.

"ANALOG COMPUTER SIMULATION OF TRAILING VORTEX EFFECTS ON FOLLOWING AIRCRAFT"

M.S. Thesis, May 1971, Iowa State University, Ames, IA

The vortex effects on a penetrating aircraft are simulated using an analog computer. The mode of penetration considered is in an along-track fashion in which the following aircraft flies parallel to the trail of the vortices. A C-130 aircraft probing the vortex wake of another C-130 and the wake of a C-5A was investigated. It was found that the encounter aircraft experienced the largest violent response when the initial positioning of the aircraft was at approximately 0.4 wing span to the right or to the left

of the vortex center. A sharp decrease in the response was experienced when the aircraft was initially displaced above or below the vortex trail.

Bernstein, S. and Iversen, J. D.

"DYNAMIC SIMULATION OF AN AIRCRAFT UNDER THE EFFECT OF VORTEX WAKE TURBULENCE"

Proceedings of 2nd Atmospheric Flight Mechanics Conf., NASA Ames Research Center, September 1972, pp. 29.1-29.9

A technique is developed to simulate the response of a trailing aircraft due to the induced rolling moments and loss of lift imposed by the vortices. Results of such a simulation for the case of a C-130 behind another C-130 and behind a C-5A are presented.

Berselli, L. C. and Gubinelli, M.

"ON THE GLOBAL EVOLUTION OF VORTEX FILAMENTS, BLOBS, AND SMALL LOOPS IN 3D IDEAL FLOWS"

Communications in Mathematical Physics, Vol. 269, 2007, pp. 693-71.

We consider a wide class of approximate models of evolution of singular distributions of vorticity in three dimensional incompressible fluids and we show that they have global smooth solutions. The proof exploits the existence of suitable Hamiltonian functions. The approximate models we analyze (essentially discrete and continuous vortex filaments and vortex loops) are related to some problems of classical physics concerning turbulence and to the numerical approximation of flows with very high Reynolds number. Finally, we apply our strategy to discrete models for filaments used in numerical models.

Bertenyi, T.

"MERGER OF AIRCRAFT WAKE VORTICES"

Thesis, November 2001, University of Cambridge, Cambridge, UK, p. 180

In the current study, vortex merger is investigated experimentally using a wake survey to provide quantitative measurements. Two lift-producing wings are used to generate the vortices and time to vortex merger is parameterized as a function of initial separation and circulation ratio. The evolution of the two vortices throughout the initial interaction, merger, and post-merger phases is quantified. During the initial interaction, the vortices bloom and draw together until a critical separation is reached at which point merger occurs rapidly. The resulting merged vortex has an altered structure but no significant amounts of circulation are destroyed. Characteristics of the merging process are identified and it is observed that the merging mechanism of nominally equal vortices is different than that of unequal strength vortices. In the case of two unequal strength vortices, the weaker vortex is strongly distorted during the initial interaction phase. Furthermore, unequal strength vortices reach the merger phase earlier and thus present a reduced time to merger compared to equal strength vortices.

Increased freestream turbulence is seen to enhance the rate of blooming thus also reducing the time to merger. Two-dimensional Euler and Navier Stokes computational simulations served as investigative tools and allowed for a direct comparison between the experimental data and two-dimensional vortex merger. It was shown that the assumption of two-dimensionality is inadequate for modelling the correct rate of vortex blooming and the drawing together of the vortices. It was concluded that the initial interaction between merging vortices is three-dimensional.

Bertenyi, T. and Graham, W.

"AN EXPERIMENTAL STUDY OF THE MERGING OF AIRCRAFT WAKE VORTICES"

AIAA Paper No. 2000-4129, Denver, CO, August 2000

This report presents the results of an experimental study of the merger of co-rotating aircraft wake vortices. Two lifting wings were used to generate a pair of co-rotating vortices in a wind tunnel and a single-tube yawmeter was traversed in planes behind the wing to provide both qualitative and quantitative observations. In the case of vortices of nominally equal circulation, they were seen to co-orbit, draw closer together and then very quickly merge. If the two vortices were of different strengths, the merger process took longer, as the smaller vortex was first distorted and wrapped around the larger. During this process, vorticity was bled from the smaller to the larger vortex. The actual distance to merger for a given initial separation of two nominally equal vortices was seen to collapse onto a single curve once the variables were properly non-dimensionalized. For similarly non-dimensionalized but distinctly non-equal vortices, merger was complete at an earlier point. A simple vortex blob numerical simulation method is able to provide a good description of the merger process, suggesting that the flow is essentially two-dimensional and inviscid.

Bertenyi, T. and Graham, W. R.

"EXPERIMENTAL OBSERVATIONS OF THE MERGER OF CO-ROTATING WAKE VORTICES"

J. Fluid Mech., Vol. 586, 2007, pp. 397-422

The interaction and merger of a pair of co-rotating vortices has been studied experimentally in a wind tunnel. The vortices are generated using two separate wings, allowing both initial circulation ratio and initial separation to be varied. At the nominal test speed of 30 m/s, the circulation-based Reynolds number is typically 64,000. Mean crossflow velocities at stations downstream are obtained with a traverse-mounted yaw meter. The vortex interaction is characterized by fitting Lamb-Oseen profiles to the measured, azimuthally averaged, tangential velocity profiles. It is found that the merger process differs in several important respects from lower-Reynolds-number studies. First, the separation of the vortices decreases continually throughout the initial, 'viscous growth', phase, instead of remaining constant. Second, the vortex core growth in this phase appears to be greater than can be accounted for by turbulent diffusivity, even after correcting for the effects of wandering. Finally, the time to merger lies well below that predicted by expressions based on the lower-Reynolds-number observations, and is further reduced when the circulation ratio departs from unity. We conclude that

the enhanced core growth is probably due to the short-wavelength 'elliptic' instability that has already been observed in some high-Reynolds-number experiments. The mechanism behind the decrease in separation, which is a crucial factor in the reduced merger time, is three-dimensional, but, beyond this, remains unknown.

Berthet, R., Fauve, S. and Labbe, R.

"STUDY OF THE SOUND-VORTEX INTERACTION: DIRECT NUMERICAL SIMULATIONS AND EXPERIMENTAL RESULTS"

Eur. Physical J., Vol. B32, 2003, pp. 237-242

We present a study of sound propagation through a single vortex by direct numerical simulations (DNS) compared to experimental measurements. We analyze the amplitude and the phase shift of the sound wave when it interacts with the vortical flow and we display the focusing effects produced by the vortex. We show that the turbulent fluctuations have a little effect on the sound phase shift whereas they induce a strong defocusing effect on the sound amplitude.

Bertin, J. J. and Westkaemper, J. C.

"SCALE-MODEL STUDIES OF BLAST-DEFLECTION FENCES FOR HIGH THRUST ENGINES"

Journal of Aircraft, Vol. 9, No. 6, June 1972, pp. 445-446.

A 0.02 scale model was constructed to represent a twin-engine aircraft, the proposed fence geometries, and the adjacent service roads requiring traffic protection. Data were obtained to define the flowfield immediately upstream of the fence and downstream to the roads. In addition to a single, long primary fence, flow field data were obtained for double fences in which a smaller, auxiliary fence was located upstream of the primary fence to provide a sheltered area for ground service equipment. Results of the experimental investigation are presented.

Bertrand, X.

"PARAMETRIC EFFECTS ON SPOILER GEOMETRY ASSESSMENT WITH CHIMERA TECHNIQUE"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-199, September 2007, pp. 3153-3161.

This paper presents the use of CFD methods based on RANS equations and Chimera technique to simulate the flow on a transport aircraft with deployed spoilers to improve the physical understanding of these control surfaces. The first part of the paper explains spoiler aerodynamics and their interactions with the wings, HTP and VTP. Then, spoiler geometry is modified as a function of various parameters (position on wing span and chord, hinge line sweep, spoiler chord size) and the impact of these geometrical effects on handling qualities coefficients is detailed.

Besson, C., Dolfi-Bouteyre, A., Canat, G., Cezard, N., Augere, B., Durecu, A., Lombard, L., Valla, M. and Hallermeyer, A.

"DOPPLER LIDAR DEVELOPMENTS FOR AERONAUTICS"

ONERA Aerospace Lab Journal, Issue 12, December 2016, pp. 1-16.

Detecting atmospheric hazards such as wake vortices, turbulences, wind shear or wind gusts would improve flight and airport traffic safety. Moreover, to face the current and future challenges of air traffic growth in terms of environment, safety, and costs, one of the major challenges is to increase runway throughput by optimizing the distance separation between aircraft. These are some of the issues, among others, addressed by Doppler LIDARs. This powerful technique can provide remote air speed data and is being deployed on the ground or in flight. The paper presents some of the recent Doppler LIDAR developments at ONERA. Some insight into state-of-the-art technology is provided, as well as perspectives for future applications in aeronautics.

Besson, C., Valla, M., Canat, G., Augere, B., Fleury, D., Goular, D., Cariou, J. P., Dlofi-Bouteyre, A., Brousmitche, S., Lugan, S., Bricteux, L. and Macq, M.

"PULSED 1.5-MICRON LIDAR FOR AXIAL AIRCRAFT WAKE VORTEX DETECTION"

15th Coherent Laser Radar Conf., Toulouse, France, June 2009.

We present the development of an axial aircraft wake vortex Lidar sensor working in Mie scattering regime and based on a pulsed 1.5-micron fiber laser. An end-to-end Doppler heterodyne Lidar simulator is used for the Lidar design. The simulation includes the observation geometry, the wake vortex velocity image, the scanning pattern, the Lidar instrument, the wind turbulence outside the vortex, and the signal processing. A Doppler heterodyne Lidar is developed with an innovative high brightness pulsed 1.5 micron laser source, based on a MOPFA architecture with a special large core fiber amplifier. The Lidar includes a real time display of the wind field. Wind dispersion is post-processed. Field tests carried out at Orly airport in April 2008 are reported. Axial aircraft wake vortex signatures have been successfully observed and acquired at a range of 1.2 km with an axial resolution of 75 m for the first time with a fiber laser source.

Bethke, N. and Dalziel, S. B.

"RESUSPENSION ONSET AND CRATER EROSION BY A VORTEX RING INTERACTING WITH A PARTICLE LAYER"

Physics of Fluids, Vol. 24, 2012, pp. 063301-1 - 063301-31.

This paper presents results from an experimental investigation of the interaction of a vortex ring with a particle layer. The flow dynamics during the onset of particle resuspension are analyzed using particle image velocimetry, while a light attenuation method provides accurate measurements of the final

eroded crater shape. This work is a continuation of the research described by Munro, Bethke and Dalziel, 'Sediment resuspension and erosion by vortex rings' which focused on the general resuspension onset dynamics and initial crater formation. Here, we analyze the velocity induced by the vortex ring on the particle layer surface during the resuspension of particles for different particle sizes, and the shape and size of the final craters that are formed by the impact of the vortex ring. We find that the boundary condition is characterized by a quasi-slip velocity at the particle layer surface, independent of the particle size. The particle diameter, and thus bed permeability, is found to have a significant effect on the final crater characteristics.

Betyaev, S. K.

"NONLINEAR THEORIES OF THE LAMINAR COLUMNAR VORTEX"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 100-108

Exact and approximate solutions are proposed to the problem of the temporal and spatial evolution of the columnar vortex based on the Euler and Navier-Stokes equations. Unlike the linear theory of the thin columnar vortex, the nonlinear theory proposed has the main terms of the expansion (in terms of a small parameter characterizing the vortex width) that already take into consideration longitudinal gradients. It has been shown that the bilinear Euler equation allows both exponential and sinusoidal expansion of variables. Separation of variables in the Navier-Stokes equation is possible for the flow with constant velocity gradient. In this case a singularity of the solution was revealed along with its non-continuability into the domain adjacent to the vortex axis. [In Russian.

Betyaev, S. K.

"MATHEMATICAL MODELING IN TRAILING VORTEX DYNAMICS"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 22-40

The paper is intended to be a fast introduction to trailing-vortex dynamics. Problems associated and hierarchy levels of their description are categorized, the principles of constructing mathematical models and physical prerequisites underlying the theory are discussed. Preference is given to correlating dissimilar phenomena and establishing new relations between seemingly remote and isolated facts with primarily emphasizing the methodology rather than the 'formulism'. [In Russian.

Betyaev, S. K.

"MATHEMATICAL MODELS OF THE FAR VORTEX WAKE"

In: Flight Safety, Aircraft Vortex and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 125-147

The asymptotical analysis has enabled us to develop a model for the transverse structure of an axisymmetric columnar vortex in an incompressible fluid including the wall sublayer with dominating viscous and turbulent stresses, buffer zone with dominating turbulent stresses, buffer zone with dominating turbulent stresses and inertia, and the region of velocity and circulation defects, where the inertial terms prevail. For each of these regions, equations are obtained for averaged quantities, which remain nonclosed since the type of Reynolds stresses is unknown. Thicknesses of these regions depend on characteristic values of velocity fluctuations. A turbulence model in the Trefftz plane has been considered, where the nonlinearity is degenerated into a recurrently solvable one. A method of averaging over the circumferential coordinate was developed to solve a problem on asymmetric vortex evolution. Flow topology was investigated in the problem of diffraction of a thin vortical flow by a plate and its solution was obtained in an extremely simplified approximation.

Betyaev, S. K.

"ON THE EFFECT OF LAMINAR BOUNDARY LAYER SUCTION ON THE WING VORTEX SYSTEM"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 68-78

The classification of the mathematical models of suction is given, its concepts and influence on the aircraft wake are discussed. The conditions of appearing a secondary flow separation are considered and the optimum suction speed distribution required for preventing the separation is determined. The suction of inviscid fluid is shown to be capable of eliminating the original cause of the secondary separation - the pressure gradient singularity, and the suction speed distribution optimum for this purpose is determined.

Betyaev, S. K.

"HOW TO CUT A VORTEX FILAMENT?"

Fluid Dynamics, Vol. 36, No. 2, 2001, pp. 262-26.

The conditions of linear theory applicability, as well as the conditions under which the contact discontinuity effect can be neglected, are derived. The topology of the trajectories in the problem of thin vortex-jet diffraction on a plate is studied and the analytical solution of a maximally simplified version of the problem is obtained. An asymptotically rigorous model of an equivalent vortex in the form of a narrow high-velocity jet is proposed.

Betyaev, S. K.

"MATHEMATICAL MODELING OF THE COLUMNAR VORTEX"

Theoretical Foundations of Chemical Engineering, Vol. 34, No. 5, 2000, pp. 423-427

The columnar laminar vortex has a two-zone structure in the case of a highly swirling flow. Various asymptotics for the laminar, wave, and turbulent flows in the Trefftz plane are discussed.

Betz, A.

"VORTICES AND THE RELATED PRINCIPLES OF HYDRODYNAMICS"

NACA TN-68, November 1921, NACA Langley Aero. Lab., Langley Field, VA. (Also, Zeitschrift fur Flugtechnik und Motorluftschiffahrt, July 15, 1921.)

Here, conceptions concerning vortices are illustrated by the simplest possible examples. Mathematical formulas and similar means of presentation, which, for the most part, do not help the understanding of persons not versed therein, have been avoided as much as possible. Instead, the author has endeavored to demonstrate the phenomena by means of simple geometrical and mechanical illustrations. For the sake of clarity, the author chiefly considers currents in one plane only, a situation that can be readily represented by diagrams. Some of the peculiarities of vortices in three-dimensional flow are briefly discussed.

Betz, A.

"BEHAVIOR OF VORTEX SYSTEMS"

Zeit. fur angewandte Math. und Mech., Vol. 12, No. 3, June 1932, pp. 164-174. (Also, NACA TM-713, June 1933.)

Progressive application of the Kutta-Joukowski theorem to the relationship between airfoil lift and circulation affords a number of formulas concerning the conduct of vortex systems. The application of this line of reasoning to several problems of airfoil theory yields an insight into many hitherto little observed relations. The report is confined to plane flow, hence all vortex filaments are straight and mutually parallel.

Bevan, J. J. and Willis, D. J.

"A HIGH-ORDER CONSERVATIVE EULERIAN SIMULATION METHOD FOR VORTEX DOMINATED FLOWS"

AIAA Paper 2016-3349, June 2016, Washington, DC.

A high-order, conservative Eulerian method is presented for the simulation of vortex dominated inviscid fluid flows. The primitive variable incompressible Euler equations are recast in the velocity-vorticity form to explicitly enforce conservation of vorticity. The advection of the vorticity is then calculated via a two-step process: the velocity field is determined by evaluation of the Biot-Savart integral, and then a line-based discontinuous Galerkin (DG) Eulerian spatial discretization scheme is applied to accurately advect the vorticity field. The accuracy and convergence of this method was examined for test cases where an analytical solution exists, as well as more challenging test cases which lack an analytical solution. The convergence rate behavior is chiefly controlled by the error in the

calculated velocity field. Velocity errors are due to two factors: the approximation of the Biot-Savart integral with a desingularized form, and reduced quadrature convergence for the nearly singular integral. Solver parameters were chosen to balance these two effects resulting in nearly optimal convergence of the overall method in the analytical test, and high-order convergence in the qualitative test case.

Beves, C. C. and Barber, T. J.

"THE WINGTIP VORTEX OF A DIMPLED WING WITH AN ENDPLATE"

Journal of Fluids Engineering, Vol. 139, February 2017, pp. 021202-1 - 021202-9.

Dimples used as sub-boundary layer vortex generators have been shown to reduce wake size at large angles of incidence. The effect these dimples have on wingtip vortices with an endplate is measured via laser Doppler anemometry (LDA) on an inverted Tyrrel11026 airfoil ($Re = 5000$ and chord = 0.075 m) in ground effect to determine the flow characteristics for this configuration and to see if previous measurements were performed in a thinner part of the wake due to any potential wake waviness. The strength of the wingtip vortex for the dimpled wing is 10 percent higher than the 'clean' wing immediately downstream. The clean wing has large region of high turbulence throughout the wake, and the dimples reduce this by 50 percent. The net result is that dimples drastically improve the flow in the wake of the wing and endplate.

Bezrodnov, A. V., Gaifullin, A. M., Soudakov, G. G., Soudakov, V. G., Voyevodin, A. V. and Zakharov, S. B.

"INVESTIGATIONS INTO THE WAKE VORTEX EVOLUTION DOWNSTREAM THE A300 AIRCRAFT MODEL"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 84-94

Experimental flow field data processing was made to obtain the vortex wake characteristics, such as vortex core radius, vortex core circulation and vortex position. Two programs (ZONWAKE and ENGWAKE) for wake parameters calculation were validated through this experimental data processing.

Bezrodnov, A. V., Koshcheyev, A. V., Markachev, Y. Y., Plekhanov, Y. A. and Yegorov, B. V.

"DIAGNOSTICS OF EXHAUST JETS AND AIRCRAFT VORTICES WITHIN THE MILLIMETER- AND SUBMILLIMETER-WAVE BANDS"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 346-365

The updated theoretical expression for an absorption coefficient of radiation by dimers considering the modern data on their structure and experimental results has allowed one to conclude, that in the window of transparency of the atmosphere in the range of reciprocal wavelength of 7 to 8 reciprocal

cm in the vortex wake behind an airplane the controlling factor is the dimer mechanism of an absorption of millimetric and submillimetric radio waves.

Bezrodnov, A. V., Markachev, Y. Y. and Yegorov, B. V.

"FORMATION OF WATER VAPOR MOLECULAR CLUSTERS IN AIRCRAFT VORTEX WAKE"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 340-345

The paper deals with the formation of water vapor molecular clusters in the aircraft wakes. Distributions of temperature and molar fraction of water dimers over a wake section are determined for two fluid-mechanical models: the Lamb-Rankine vortex and three-zone vortex model (Gaifullin et al. 1996). The dependence of water dimer molar fraction on flow humidity and temperature is obtained. Distribution of maximum water dimer molar fraction along the wake center line is determined for various atmospheric conditions. Studied separately is the dependence of clusters concentration on humidity, which may be employed to account for the condensation effect in the wake.

Bhagwat, M. and Leishman, J. G.

"TIME-ACCURATE FREE-VORTEX WAKE MODEL FOR DYNAMIC ROTOR RESPONSE"

Aeromechanics 2000, American Helicopter Society, November 2000, Atlanta, GA.

A time-accurate free-vortex method was developed to accurately predict the time evolution of rotor inflow during various transient, maneuvering flight conditions. Because of the highly non-linear nature of the problem, free-vortex wake solutions are often susceptible to numerical instabilities. Therefore, the new algorithm was examined for stability, accuracy and convergence. The rotor wake in near hovering wake is known to be inherently unstable and, therefore, the stability of the numerical algorithm is the most important criteria to ensure convergence. Solution convergence of the algorithm was demonstrated in steady-state conditions, with a verified second-order accuracy for both hovering and forward flight. This algorithm was then applied to help understand the rotor response during a step or a ramp increase in collective pitch. A slow build-up of inflow (a time lag) was found from the dynamic evolution of the trailed wake structure. The methodology was also successfully applied to transient axial and inclined descending flight through the highly unsteady vortex ring state.

Bhagwat, M. and Leishman, J. G.

"ON THE AERODYNAMIC STABILITY OF HELICOPTER ROTOR WAKES"

56th Annual Forum, American Helicopter Society, Virginia Beach, VA, May 2000

An eigenvalue analysis has been developed to study the stability of helicopter rotor wakes in hover and axial flight. The results are supported with observed trends from hovering rotor wake experiments. The rotor wake is shown to be intrinsically unstable, with the tip vortices exhibiting several possible

unstable deformation modes. The wake divergence (instability) rate associated with each deformation mode depends on the relative phase of the perturbations produced on tip vortex filaments generated by different blades. Wake divergence rates increase sharply after the initial radial contraction of the wake below the rotor, and is confirmed by experimental observations. The divergence rates are governed by the vortex-induced velocities; the divergence rate for any deformation mode decreases with increasing rotor thrust, and with increasing climb rate. The so-called tip vortex 'pairing' phenomenon, sometimes empirically observed in hovering flight conditions, is shown to be a particular unstable long-wave deformation mode of the rotor wake. It is further shown that in numerical solutions of the wake using free-vortex wake methods this deformation mode can be artificially excited by numerical errors. A proper choice of numerical time integration algorithm is necessary to prevent non-physical growth of these numerical errors.

Bhagwat, M. J. and Leishman, J. G.

"CORRELATION OF HELICOPTER ROTOR TIP VORTEX MEASUREMENTS"

AIAA Journal, Vol. 38, No. 2, February 2000, pp. 301-308.

The roll-up and development of the tip vortices generated by subscale helicopter rotors were measured and analyzed. The measurements were performed on one- and two-bladed hovering rotors using three-component laser Doppler velocimetry. A trip strip was used to simulate boundary-layer transition at the higher Reynolds numbers typical of the full-scale rotor. The detailed velocity field of the tip vortex was investigated, a strong self-similarity of the swirl velocity profile being found. The measurements suggest a general logarithmic growth of the viscous core, which for older vortex ages is proportional to the square root of time (vortex age). Measurements from other helicopter rotor and fixed-wing experiments are used to support the observations.

Bhagwat, M. J. and Leishman, J. G.

"MEASUREMENTS OF BOUND AND WAKE CIRCULATION ON A HELICOPTER ROTOR"

Journal of Aircraft, Vol. 37, No. 2, March-April 2000, pp. 227-234

High-resolution measurements of the three-dimensional velocity field around the blade and in the wake of a small-scale hovering rotor were made using three-component laser Doppler velocimetry. The tip-vortex circulation strength was determined from velocity field measurements in the rotor wake. The spanwise circulation distribution was estimated from the velocity field measurements around each spanwise blade section. It is shown that for helicopter rotors it is difficult to exclude the effects of the returning wake vorticity from contours that enclose the blade section, making unique, grid-independent, bound circulation measurements possible only under very specific conditions. The connection between blade circulation loading and the tip-vortex circulation was also examined. For the configurations studied the initial circulation strength of the tip vortices was found to be approximately 70% of the estimated peak circulation on the blades.

Bhagwat, M. J. and Leishman, J. G.

"NUMERICALLY EFFICIENT FREE VORTEX WAKE SOLUTIONS USING HIGHER-ORDER EXTRAPOLATION"

J. American Helicopter Society, Vol. 47, No. 4, October 2002, pp. 297-302

The increasing predictive success of free vortex wake models for rotor analyses has sparked an interest in improving their computational efficiency and decreasing computing costs to facilitate more routine applications. In this article, techniques to improve the numerical efficiency of discrete free vortex wake models are discussed. The impact of reduced computational costs on the accuracy and convergence characteristics of the wake solution is examined. The numerical efficiency is estimated based on reducing numerical errors corresponding to the associated computational costs. A new technique, based on Richardson's extrapolation, is shown to reduce the computational costs by improving the order of accuracy of the solution. This technique can be applied to obtain a more accurate prediction of the wake induced velocities, as well as to obtain a higher-order wake geometry solution. The higher order solution is shown to be numerically more efficient, with an improved ratio of numerical errors to computational cost.

Bhagwat, M. J. and Leishman, J. G.

"SELF-INDUCED VELOCITY OF A VORTEX RING USING STRAIGHT-LINE SEGMENTATION"

Journal of the American Helicopter Society, Vol. 59, 2014, pp. 012004-1 to 012004-7.

The accuracy of discretized induced velocity calculations that can be obtained using straight-line vortex elements has been reexamined, primarily using the velocity field induced by a vortex ring as a reference. The induced velocity of a potential (inviscid) vortex ring is singular at the vortex ring itself. Analytical results were found by using a small azimuthal cutoff in the Biot-Savart integral over the vortex ring and showed that the singularity is logarithmic in the cutoff. Discrete numerical calculation showed the same behavior, with the self-induced velocity exhibiting a logarithmic singularity with respect to the discretization, which introduces an inherent cutoff in the Biot-Savart integral. Core regularization or desingularization can also eliminate the singularity by using an assumed 'viscous' core model. Analytical approximations to the self-induced velocity of a thin-cored vortex ring have shown that the self-induced velocity has a logarithmic singularity in the core radius. It is further shown that the numerical calculations require special treatment of the self-induced velocity caused by the curvature, which is lost by the inherent cutoff in the straight-line discretization, to correctly recover this logarithmic singularity in the core radius. Numerical solution using straight-line vortex segmentation, augmented with curved vortex elements only for the self-induced velocity calculation, is shown to be second-order accurate in the discretization.

Bhagwat, M. J. and Leishman, J. G.

"GENERALIZED VISCOUS VORTEX MODEL FOR APPLICATION TO FREE-VORTEX WAKE AND AEROACOUSTIC CALCULATIONS"

The development of a generalized viscous vortex model is described for application in rotor aero-acoustic analyses. A summary is given of previous models for the viscous core growth and induced velocity field of a trailing tip vortex. The assumptions made for the vortex core growth are shown to influence the predictions of the rotor wake geometry, as well as the induced velocities, air loads, and performance, thereby emphasizing the need for a more universal and physically representative vortex model. In the present approach, the viscous core growth was modeled using an extension of the classic Lamb-Oseen model for the diffusion of laminar vortices. Turbulence in the tip vortex affects the diffusion of vorticity, and these effects were incorporated using an empirically validated correction for the average apparent or 'eddy' viscosity. The vortex induced velocity profiles measured in experiments were found to exhibit strong self-similarity when using the vortex core radius as a length-scale, suggesting that a generalized model is possible. A family of algebraic models for the swirl, axial, and radial components of the velocity induced by a viscous trailing tip vortex is proposed. These velocity components were found from a solution to a simplified form of the incompressible Navier-Stokes equations. The velocity profiles are written in terms of a single integer exponent with the viscous core growth being given by a semi-empirical relation for the turbulent viscosity that scales as a function of the vortex Reynolds number. The model is compared with velocity field measurements for both fixed-wing and rotating-wing tip vortices, with good agreement.

Bhagwat, M. J. and Ramasamy, M.

"EFFECT OF TIP VORTEX APERIODICITY ON MEASUREMENT UNCERTAINTY"

Experimental Fluids, Vol. 53, 2012, pp. 1191-1202.

Vortex aperiodicity introduces random uncertainty in the measured vortex center location. Unless corrected, this may lead to systematic uncertainty in the vortex properties derived from the measured velocity field. For example, the vortex core size derived from averaged or mean flow field appears larger because of aperiodicity. Several methodologies for aperiodicity correction have been developed over the past two decades to alleviate this systematic uncertainty. However, these do not always reduce the accompanying random uncertainty. The current work shows that the analysis methods used to derive the vortex properties from the measured velocity field play an important role in the resultant random uncertainty in these properties; perhaps, even more important role than the aperiodicity correction methodology itself. It is hypothesized that a class of methods called global methods, which use a large extent of measured data, yield a smaller measurement uncertainty compared to local methods. This hypothesis is verified using a newly proposed global method based on a planar least-squares fit. The general applicability of the method is demonstrated using previous particle image velocimetry measurements of rotor tip vortices. The results clearly demonstrate a reduced random uncertainty in the vortex core properties, even in the presence of secondary vortical structures. Furthermore, the results are independent of the choice of aperiodicity correction methodology.

Bhagwat, M. J., Leishman, J. G. and Martin, G. L.

"TRANSIENT ROTOR INFLOW USING A TIME-ACCURATE FREE-VORTEX WAKE MODEL"

AIAA Paper No. 2001-0993, Reno, NV, January 2001

A time-marching free-vortex wake analysis was developed for application to the prediction of the aerodynamics of a helicopter rotor under transient or maneuvering flight conditions. The stability, accuracy and convergence of the time-marching algorithms was rigorously examined. A linearized analysis was used to determine the basic stability characteristics of the algorithms. A new time-marching algorithm is proposed to ensure numerical stability and convergence of the wake solution. The second-order accuracy and grid independent nature of the wake geometry solution is demonstrated. This algorithm is applied to the problem of transient rotor response resulting from time-varying changes in the rotor collective pitch inputs. Good agreement is shown between the predictions and experimental measurements.

Bhagwat, M. J., Ramasamy, M. and Caradonna, F. X.

"FUNDAMENTAL CHARACTERIZATION OF SPANWISE LOADING AND TRAILED WAKE VORTICES"

SR-RDMR-AD-16-02, July 2016, US Army Research, Development, and Engineering Command, Redstone Arsenal, AL.

This report focuses on one of the most prominent flow features of the hovering rotor wake, the close interaction of the tip vortex with a following blade. Such vortex interactions are fundamental determinants of rotor performance, loads, and noise. Yet, they are not completely understood, largely due to the lack of sufficiently comprehensive experimental data. The present study aims to perform such comprehensive measurements, not on hovering helicopter rotors (which hugely magnifies test complexity) but using fixed-wing models in controlled wind tunnel tests. The experiments were designed to measure, in considerable detail, the aerodynamic loading resulting from a vortex interacting with a semi-span wing, as well as the wake resulting from that interaction. The goal of the present study is to answer fundamental questions such as (a) the influence of a vortex passing below a wing on the lift, drag, tip vortex and the wake of that wing, and (b) the strength of the forming tip vortex and its relation to the wing loading and/or the tip loading.

Bhaskaran, S. and Calhoun, R.

"AIRCRAFT VORTEX CHARACTERIZATION BY ESTIMATING THE DOMINANT MODES FROM THE RETURN POWER SPECTRUM OF A DOPPLER LIDAR"

AIAA Paper 2017-4240, June 2017, Denver, CO.

A new exploratory approach for aircraft vortex tracking is presented in this paper. The 'Dominant Modes Estimation' technique is a promising motivation to improve the accuracy with which we locate the vortex core position. Using the lidar simulator in tandem with the analytical vortex model defined in section II, we can simulate the Doppler spectrum estimate for different lidar system parameter settings, like the lidar signal to noise ratio and also vortex characteristics like the core radius and

circulation strength, depending on the aircraft type. The algorithm is a step towards accurate vortex parameter estimation. When compared with other techniques like the method of velocity envelope the new approach estimates the spectral width by choosing an appropriate model instead of the traditional unimodal Gaussian spectrum. The choice of a bi-model Gaussian spectra was justified based on the spectrum estimate simulated using the Doppler lidar simulator. The new model is a first step towards more efficient and accurate estimation of vortex parameters. A more detailed analysis on real data collected using a Doppler lidar is necessary to compare its performance with other existing methods.

Bhattacharya, S.

"EXACT ANALYTICAL SOLUTIONS FOR STEADY THREE-DIMENSIONAL INVISCID VORTICAL FLOWS"

Journal of Fluid Mechanics, Vol. 544, 2007, pp. 147-162.

Vortical flows with an axial swirl and a toroidal circulation can be observed in a wide range of fluid mechanical phenomena such as flow around rotary machines or natural vortices like tornadoes and hurricanes. In this paper, we obtain exact analytical solutions for a general class of steady systems with such three-dimensional circulating structures. Assuming incompressible ideal fluid, a general single-variable equation, known as the Squire-Long equation, can be constructed which can uniquely describe the velocity fields with steady axial and toroidal circulations. In this paper, we consider the case where this type of flow can be analyzed by solving a linear homogeneous partial differential equation. The derived equation resembles the governing equation of the hydrogen problem. As a result, we obtain a quantization relation which is similar to the expression for the quantized energy states in a hydrogen atom. For circulating flows, this formalism provides a complete set of orthogonal basis functions which are regular and localized. Hence, each of the basis solutions can be used as a simplified model for a realistic phenomenon. Moreover, an arbitrary circulating field can be expanded in terms of these orthogonal functions. Such an expansion can be potentially useful in the study of more general vortices.

Bhattacharyya, S. and Conlisk, A. T.

"THE STRUCTURE OF THE ROTOR WAKE IN GROUND EFFECT"

AIAA Paper No. 2003-1255, Reno, NV, January 2003

The form of the rotor wake in presence of a ground has been investigated through a simplified approach. Both hover and forward speed of the rotor have been considered. The presence of the ground is modeled using the method of images. A lifting-line theory is used to model each rotor blade and a time-stepping vortex method has been used to obtain the evolution of tip-vortex. The agreement of our computed results with the experimental data due to Light in hover with IGE is encouraging. The wake geometry for both single and two bladed rotors has been calculated for different ground to rotor separation distance and for several forward flight speeds. The form of the ground vortex in proximity of ground in the low speed forward flight of the rotor has been studied. Our

results show that the size of the ground vortex reduces and the vortex core shifts downstream as the forward speed of the rotor increases.

Biava, M. and Vigeveno, L.

"ASSESSMENT OF THE VORTICITY CONFINEMENT TECHNIQUE APPLIED TO ROTORCRAFT FLOWS"

AIAA Paper No. 2003-3524, Orlando, FL, June 2003

The application of the vorticity confinement technique to single-blade rotorcraft simulations, both in hovering and forward flight conditions, allows to improve the representation of certain features of the flow field but has a very limited influence on the predicted thrust. Comparison with experimental sectional blade loads shows localized improvements, mainly in the central region of the retreating blade.

Biblarz, O.

"THINGS YOUR BAB (BASIC AERODYNAMICS BOOK) NEVER TOLD YOU"

AIAA Paper 1994-0849, January 1994, Reno, NV.

Standard coverage in basic aerodynamic books tends to be deficient in detail. The author picks 4 topics where missing detail can be counter-productive. Dimensional analysis as used to derive the force coefficient must begin with a three-dimensional wing; this has the added advantage of bringing out the aspect ratio (AR) directly. Inviscid flow equations can be used to calculate lift but lift originates from the circulation which is produced by viscous interactions. At angles of attack above 15 degrees, this airfoil theory requires modifications which still yield the very useful, closed form solutions of this theory as indicated in the paper. Finally, the aerodynamic center is shown to be at the quarter-chord location via a direct manipulation of thin-airfoil theory results.

Biehl, K. J., Teager, S. A. and Tymczyszyn, J. J.

"FLIGHT TEST INVESTIGATION OF THE WAKE VORTICES GENERATED BY HELICOPTERS"

Cockpit, October-December 1991, pp. 5-22

Helicopter wake vortices were probed by small airplanes to acquire direct assessment of vortex danger as a function of distance behind the generating helicopter. The flight tests were planned to provide data for establishing ATC separation criteria and for comparison with theoretical calculations. Ground based tests indicate a very high vortex hazard from helicopters and therefore imply very large separation distances for safe IFR flight behind rotorcraft. These tests are deemed valid and useful as they represent an accurate duplication and analysis of real-world wake vortex hazards of helicopters in forward flight.

Bieniawski, S. R., Clark, R. W., Rosenzweig, S. E. and Blake, W. B.

"SUMMARY OF FLIGHT TESTING AND RESULTS FOR THE FORMATION FLIGHT FOR AERODYNAMIC BENEFIT PROGRAM"

AIAA Paper 2014-1457, January 2014, National Harbor, MD.

The Air Force Research Lab and DARPA have been investigating the challenges and opportunities associated with flying aircraft in formation for aerodynamic benefit. Under the Surfing Aircraft Vortices for Energy (SAVE) concept, aircraft are flown autonomously at longitudinal separations of 3000-8000 ft at offsets from the wake sufficient to obtain significant aerodynamic benefit. Flight test of the enhanced auto-pilot to accomplish this was demonstrated in Oct. 2012, obtaining a savings of 5-10 percent fuel burn and capturing data on the effects on the airframe, engines, and aircrew for a representative transport aircraft, the C-17. Additional flight tests more representative of complete missions were performed in July 2013. For extended durations greater than 90 minutes, fuel burn savings exceeded 10 percent and were accomplished fully automated. This paper will provide an overview of the flight test efforts and summarize key results.

Bieniek, D. and Luckner, R.

"SENSITIVITY ANALYSIS OF AIRCRAFT ENCOUNTERS WITH DEFORMED WAKE VORTICES"

AIAA Paper 2015-3175, June 2015, Dallas, TX.

Aging wake vortices deform due to the characteristic long-wave Crow instability. This can lead to vortex linking, breakup and the formation of vortex rings. It is generally believed that encounters of following aircraft with deformed vortices are less severe than encounters with straight vortices. However, it is not clear if this effect results directly from vortex deformation, the simultaneous reduction of vortex circulation or both. This study analyzes the sensitivity of such encounters with respect to i) the encounter scenario, ii) the level of deformation, iii) the encounter angles and iv) the location of the aircraft-vortex intersection point. The encounter severity is assessed in terms of the maximum bank angle upsets induced by the vortex flow field. Vortex shapes are based on Large-Eddy Simulations of wake vortex decay under atmospheric conditions that promote the formation of vortex rings. The reduction of encounter severity before vortex breakup is found to be less pronounced than what was concluded from previous studies. Most importantly, the location of the aircraft-vortex intersection has a strong impact on the aircraft upsets and must be accounted for in future investigations, especially when risk assessments are based on dynamic encounter simulations. When only encounters with a targeted penetration of the vortex core are analyzed, wavy vortices may even yield an increased severity prior to vortex breakup, which contradicts the assumption of continuous severity reduction with growing deformation level. After vortex breakup, aircraft upsets for most encounter parameter combinations are significantly lower than those generated by a straight vortex pair of equal strength.

Bieniek, D. and Luckner, R.

"SIMULATION OF AIRCRAFT ENCOUNTERS WITH PERTURBED VORTICES CONSIDERING UNSTEADY AERODYNAMIC EFFECTS"

AIAA Paper No. 2012-4657, August 2012, Minneapolis, Minnesota.

Today, wake turbulence related aircraft separations are a limiting factor for the capacity of airports worldwide. Detailed knowledge about the severity of potential wake encounters is necessary for a safe revision of the current ICAO separation requirements. Vortex encounter simulation is an important part in building an understanding how the encountering aircraft is adversely affected by the vortex-induced disturbances. Whereas most research has focused on aircraft encounters with a pair of straight vortices, this paper describes the simulation of encounters with perturbed vortices as they are observed under various atmospheric conditions. A method to account for unsteady aerodynamic effects during computation of vortex-induced forces and moments is presented. These effects are becoming especially important for vortex-induced disturbances of higher frequency as they appear during encounters with perturbed vortices. In combination with existing models for vortex deformation due to long-wave Crow instability, the realism of encounter simulations is increased. The simulation models are suitable for real-time and fast-time applications such as piloted simulator experiments and fast-time Monte Carlo simulations. First results of a simulator study with airline pilots are discussed.

Bieniek, D. and Luckner, R.

"INVESTIGATION OF ENCOUNTERS WITH DEFORMED WAKE VORTICES USING A MONTE-CARLO SIMULATION METHODOLOGY"

AIAA Paper 2014-2334, June 2014, Atlanta, GA.

Flight simulation is an important tool for investigating the impact of a wake-vortex flow field on aircraft response and on the severity of wake vortex encounters as it allows to evaluate a large variety of encounter parameters under controlled conditions without risk, at low costs and time-efficient. Most simulation studies have used a pair of counter-rotating straight vortices to represent the vortex wakes. However, as part of the decay process, the vortices develop a periodic long-wave deformation due to Crow instability that may lead to a breakup into vortex rings. The paper describes a methodology to perform Monte-Carlo simulations of aircraft encounters with such perturbed vortices. A high-fidelity six degree-of-freedom aircraft simulation is coupled with a wake encounter simulation that includes models of wavy vortices and vortex rings, that are fitted to wake shapes from pre-computed large-eddy simulations. Application of the methodology is demonstrated by assessing aircraft bank angle upsets from encounters with straight and deformed vortices for different test setups. First results indicate that the impact of wake deformation is strongly affected by the simulated encounter scenario. For a full-scale Monte-Carlo simulation with uniform parameter distributions and assuming the same and constant vortex strength, vortex rings exhibit a lower probability of experiencing bank angle upsets above a specific threshold, whereas only small differences between straight and wavy vortices are observed.

Bieniek, D. and Luckner, R.

"SIMULATION OF AIRCRAFT ENCOUNTERS WITH PERTURBED VORTICES CONSIDERING UNSTEADY AERODYNAMIC EFFECTS"

Journal of Aircraft, Vol. 51, No. 3, May-June 2014, pp. 705-718.

Today, wake-turbulence-related aircraft separations are a limiting factor for the capacity of airports worldwide. A detailed knowledge about the severity of potential wake encounters is necessary for a safe revision of the current International Civil Aviation Organization separation requirements. Vortex encounter simulation is an important part in building an understanding how the encountering aircraft is adversely affected by the vortex-induced disturbances. Whereas most research has focused on aircraft encounters with a pair of straight vortices, this work focuses on the simulation of encounters with perturbed vortices as they are observed under various atmospheric conditions. In addition, a method to account for unsteady aerodynamic effects during the computation of vortex-induced forces and moments is presented. These effects are becoming especially important for vortex-induced disturbances of a higher-frequency range as they may appear during encounters with perturbed vortices. This combination of models for vortex deformation due to long-wave Crow instability and unsteady aerodynamic models increases the realism of encounter simulations. The simulation models are suited for real-time and fast-time applications, such as piloted-flight-simulator experiments and fast-time Monte Carlo simulations. The results of a simulator study with airline pilots are discussed concerning the differences between encounters with straight and perturbed vortices.

Bieniek, D. and Luckner, R.

"PARAMETRIC STUDY AND SIMPLIFIED APPROACH TO WAKE VORTEX ENCOUNTER OFFLINE SIMULATION"

1st CEAS European Air and Space Conference, Berlin, Germany, September 2007, pp. 3403-3412

This paper describes the application of an existing Wake Vortex Encounter (WVE) Model in a parameter sensitivity study and in a simplified simulation. Within this model an encounter scenario is defined by a list of different parameters. The effects of a variation of these parameters on the reaction of various encountering aircraft types are being investigated and results are presented and discussed. Furthermore, a simplified approach to an offline WVE simulation is presented. Since the primary effect of a near parallel WVE is a bank angle disturbance, only roll motion is taken into consideration. The possibility of combining results from the parametric study with the simplified offline-simulation model to investigate worst case encounter scenarios is discussed.

Bieniek, D., Luckner, R., De Visscher, I. and Winckelmans, G.

"SIMULATION METHODS FOR AIRCRAFT ENCOUNTERS WITH DEFORMED WAKE VORTICES"

Journal of Aircraft, Vol. 53, No. 6, November-December 2016, pp. 1581-1596.

Simulation of aircraft wake-vortex encounters is regularly applied in the research toward revised aircraft separation minima. Most encounter flight simulation studies have used a pair of straight counter-rotating vortices. However, after being shed by the generating aircraft, the wake vortices begin to develop a growing deformation due to the long-wave Crow instability, especially under low-turbulent atmospheric conditions when vortices decay slowly. In this study, two methods for simulation of aircraft encounters with such perturbed wake vortices are described and compared. The first method uses a vortex simulation model, which is based on analytical models of the deformation that consider the large-scale vortex shapes. The second method applies vortex-velocity fields from high-fidelity large-eddy simulations. It offers the highest possible level of realism and is used as the reference. The resulting aircraft responses induced by wavy vortices and vortex rings are reproduced with good quality by the vortex simulation model. The comparison of both methods shows that the vortex simulation model captures the overall impact of vortex deformation on the aircraft upsets. It can be used for future safety assessments that require a large number of encounter simulations.

Bierach, K. F.

"WAKE VORTEX SENSING, PROCESSING AND DISPLAY"

Proceedings of 19th International Aerospace Instrumentation Symposium, Instrument Society of America, Vol. 19, 1973, pp. 153-16.

The FAA has embarked on a program to develop a wake vortex avoidance system to permit airport operations to function at optimum capacity commensurate with safety requirements. Computer modeling has identified a system concept based upon vortex prediction and detection in a closed-loop configuration. In concept, the vortex position, in defined arrival and departure corridors, is predicted from existing and projected meteorological conditions. The vortex movement is sensed within specified vertical scan planes to update this prediction. Aircraft arrivals or departures are then scheduled according to the prevailing vortex predictions and knowledge of the aircraft involved. The paper describes the system concept and potential techniques that are available to satisfy the sensor, data processing, and display subsystems requirements.

Biggers, H. C. and Orloff, K. L.

"LASER VELOCIMETER MEASUREMENTS OF THE HELICOPTER ROTOR-INDUCED FLOW FIELD"

J. American Helicopter Society, Vol. 20, No. 1, January 1975, pp. 2-10

The use of a two-color laser velocimeter to measure the flow velocities in the wake of a helicopter rotor is discussed, including methods for obtaining two components of both instantaneous and time-averaged velocities. Results are presented from an experiment using a 2.13 m (7 ft) diameter model helicopter rotor operating at a tip speed ratio 0.18 in a wind tunnel. The location of the tip vortex from the preceding blade was determined on the advancing side, and the diameter of the vortex core was found to be 15 percent of the blade chord (1.5% of the radius). The effects of the airfoil's bound

vorticity were observed in the velocity distributions very near the blade. The structure and boundary of the time-averaged wake were investigated.

Biggers, H. C., Chu, S., and Orloff, K. L.

"LASER VELOCIMETER MEASUREMENTS OF ROTOR BLADE LOADS AND TIP VORTEX ROLLUP"

31st Annual National V/STOL Forum, American Helicopter Society, Washington, DC, May 1975.

A method for obtaining and analyzing the instantaneous velocities of helicopter rotor flow fields through use of a laser velocimeter capable of simultaneously sensing two components of velocity is described. Rotor blade aerodynamic loads may be computed from the velocity distributions near the blades. The experiment was conducted with a 2.13 m (7 ft) diameter model helicopter rotor operating in a wind tunnel. Velocity distributions are presented which document the flow field near the advancing blade, circulation is calculated from the velocity measurements, and the radial distribution of circulation is discussed. The influence of the tip vortex from the preceding blade is apparent in this distribution. Tip vortex rollup on the advancing blade was documented by making a series of measurements at various distances behind the blade. Effects of blade drag are evident in the velocities behind the blade trailing edge. Methods are also discussed for determining blade section drag from these velocity measurements.

Bilanin, A. J.

"WAKE MECHANICS OF LINE VORTICES"

Ph.D. Thesis, June 1973, Mass. Institute of Technology, Cambridge, MA

Wave propagation on a vortex with a uniform axial vorticity core and a top-hat axial velocity distribution is studied and the results are a dispersion relation from which group velocities of the various modes can be calculated. A new definition of sub- and supercritical vortices based on group velocity is developed. This definition eliminates the difficulties encountered by others in determining sub- and supercritical states for asymmetric waves. Wave propagation along a vortex with slight axial inhomogeneity is developed for axisymmetric waves to introduce kinematic wave theory to vortices. Critical conditions exist along the slowly varying vortex which block the upstream propagation of waves.

Bilanin, A. J.

"COMPUTER TECHNOLOGY TO EVALUATE AIRCRAFT VORTEX WAKE INTENSITY"

SBIR-198, May 1985, Continuum Dynamics, Princeton, NJ

Existing analytical models of aircraft vortex wake dynamics have been assembled to predict the evolution and decay of two commercial jet liner wakes. The calculations undertaken demonstrate that aircraft configurational characteristics, such as engine placement and wing load distribution, can significantly influence the early stages of wake decay. This study concludes that it is currently possible

and practical to develop a computer design tool capable of assessing wake intensity for existing and future jet liners. This tool could be utilized by FAA regulators in an evaluation of separation standards for current and future aircraft, and allows airframe manufacturers to factor wake intensity into their aircraft design.

Bilanin, A. J. and Donaldson, C. duP.

"ESTIMATION OF VELOCITIES AND ROLL-UP IN AIRCRAFT VORTEX WAKES"

Journal of Aircraft, Vol. 12, No. 7, July 1975, pp. 578-585

A nonlinear model is developed which determines the swirling and axial velocities in an aircraft vortex wake, given wing lift and drag distributions. The model is shown to reduce to that given by Betz when the axial velocity is the freestream value. The nonlinear interaction of swirling and axial velocities may lead to velocity distributions which are different from those previously calculated. Qualitatively, drag reduces the axial velocity in the vortex and results in an enlarged vortex radius and, therefore, a reduction in swirl velocity. The inviscid model that predicts that significant changes in the structure of the vortex wake, brought about solely by modification of the drag distribution, may require prohibitively large drag penalties. Theoretical results compare favorably with measurements made by Orloff and Grant. A model is developed to estimate the time to roll up a two-dimensional vortex sheet. Results are presented for the cases of linear, parabolic, and elliptic wing loading.

Bilanin, A. J. and Quackenbush, T. R.

"SYSTEM AND METHOD OF VORTEX WAKE CONTROL USING VORTEX LEVERAGING"

Patent 6,042,059, 28 March 2000, Continuum Dynamics, Inc., Princeton, N. J.

This invention relates to a system and method for reducing the primary vortex wake structure generated by a lifting body mounted on an object moving through a fluid. This is achieved by first altering the generated initial vortex wake to make it vulnerable to rapid breakup; and, second, producing disturbances to this wake with secondary vortices from auxiliary lifting surfaces called vortex leveraging tabs to instigate this breakup. This invention relates to various fields of uses to include vortices generated by any type of lifting body moving through a fluid to include aircraft and watercraft such as surface vessels and submarines.

Bilanin, A. J. and Teske, M. E.

"NUMERICAL STUDIES OF THE DEPOSITION OF MATERIAL RELEASED FROM FIXED AND ROTARY WING AIRCRAFT"

NASA CR-3780, March 1984, Continuum Dynamics, Princeton, NJ

The computer code AGDISP (Agricultural Dispersal) has been developed to predict the deposition of material released from fixed and rotary wing aircraft in a single-pass, computationally efficient manner.

The formulation of the code is novel in that the mean particle trajectory and the variance about the mean resulting from turbulent fluid fluctuations are simultaneously predicted. The code presently includes the capability of assessing the influence of neutral atmospheric conditions, inviscid wake vortices, particle evaporation, plant canopy and terrain on the deposition pattern. In this report, the equations governing the motion of aerially released particles are developed, including a description of the evaporation model used. A series of case studies, using AGDISP, are included.

Bilanin, A. J. and Widnall, S. E.

"AIRCRAFT WAKE DISSIPATION BY SINUSOIDAL INSTABILITY AND VORTEX BREAKDOWN"

AIAA Paper No. 1973-0107, Washington, DC, 1973

Sinusoidal instability of aircraft trailing vortices was induced by differentially oscillating inboard and outboard flaps on a model wing in a ship towing tank. Measured amplification rates qualitatively agree with theoretical predictions. Axial velocities in the vortex core were directed toward the wing and measured to be approximately 25% of the tow speed. Vortex breakdown was observed to occur along trailers undergoing sinusoidal instability near but ahead (toward the wind) of positions of maximum trailer separation. It is shown that axisymmetric pressure gradients are imposed along the vortex core by the other sinusoidally deformed trailer and are responsible for the observed changes in core diameter. A theoretical model predicts the short-time behavior of the vortex core and shows that the response of the vortex depends crucially on the axial velocity in the vortex.

Bilanin, A. J., Donaldson, C. duP. and Snedeker, R. S.

"CALCULATION OF THE INVISCID WAKE OF A BOEING 747 AIRCRAFT"

ARAP Rept. No. 224, August 1974, Aeronautical Research Assoc. of Princeton, Princeton, NJ

A wake model based on an extension of the inviscid method of Betz used to calculate the rolled-up wake structure behind a Boeing 747 aircraft. Two aircraft flight configurations, at a lift coefficient of 1.2, are analyzed and it is shown that the inviscid wake is markedly different in structure. Comparisons between calculated and measured rolling moment on a penetrating wing show that the inviscid model provides useful estimates. When the generating aircraft is in other than the clean configuration, accurate predictions of the rolling moment will require a wake model which includes turbulent transport.

Bilanin, A. J., Donaldson, C. duP. and Snedeker, R. S.

"AN ANALYTIC AND EXPERIMENTAL INVESTIGATION OF THE WAKES BEHIND FLAPPED AND UNFLAPPED WINGS"

AFFDL-TR-74-90, September 1974, Aeronautical Research Assoc. of Princeton, Princeton, NJ

An analytic and experimental program was undertaken to define the near wake structure behind flapped and unflapped wings. The vortex wake structure is determined, given the wing lift and drag distributions with models developed in the spirit of Betz. A procedure to estimate the turbulent kinetic energy distribution in the vortex is also given, as well as a method to determine discrete vortex positions in the downstream wake.

Bilanin, A. J., Hirsh, J. E., Teske, M. E. and Hecht, A.

"ATMOSPHERIC-WAKE VORTEX INTERACTIONS"

ARAP-331, April 1978, Aeronautical Research Associates of Princeton, Princeton, NJ

The interactions of a vortex wake with a turbulent stratified atmosphere are investigated with the computer code WAKE. It is shown that atmospheric shear, turbulence, and stratification can provide the dominant mechanisms by which vortex wakes decay. Computations included the interaction of a vortex wake with a viscous ground plane. The observed phenomenon of vortex bounce is explained in terms of secondary vorticity produced on the ground. This vorticity is swept off the ground and advected about the vortex pair, thereby altering the classic hyperbolic trajectory. The phenomenon of the solitary vortex is explained as an interaction of a vortex with crosswind shear. Here, the vortex having the sign opposite that of the sign of the vorticity in the shear is dispersed by a convective instability. This instability results in the rapid production of turbulence which in turn disperses the smoke marking the vortex.

Bilanin, A. J., Snedeker, R. S. and Teske, M. E.

"INTERACTIONS AND MERGING OF LINE VORTICES"

ARAP-276, February 1976, Aeronautical Research Assoc. of Princeton, Princeton, NJ

The results of a theoretical and experimental study of the interaction between adjacent line vortices are presented. Emphasis is given to the process of merging or pairing in which two vortices of like sign coalesce to form a single vortex. Merging is discussed in terms of its importance to the growth and aging of turbulent shear layers and aircraft wakes. Flow visualization experiments are described in which merging was observed by means of smoke injected into a wind tunnel flow. Vortex pairs of like sign and equal strength, varying sign and strength, and opposite sign and equal strength were studied. Good qualitative agreement is found between the observed flow patterns and those calculated by means of a computer code.

Bilanin, A. J., Snedeker, R. S., Sullivan, R. D. and Donaldson, C. duP.

"EXPERIMENTAL AND THEORETICAL STUDY OF AIRCRAFT VORTICES"

AFOSR-TR-75-0664 and ARAP No. 238, February 1975, Aeronautical Research Assoc. of Princeton, Princeton, NJ

A review is given of development during the past five years in ARAP's study of the aircraft wake turbulence problem. Significant results are described including the successful application of the Betz roll-up method to inviscid wake calculations and its extension to multivortex wakes. Also discussed are effects due to viscous and induced drag, as well as the role of turbulence in the wake decay process. Recent results of an experimental study of a vortex flow in ARAP's vortex tube tunnel are presented including measurements of mean and turbulent velocity profiles and turbulent correlations.

Bilanin, A. J., Teske, M. E. and Curtiss, Jr., H. C.

"FEASIBILITY OF AN ONBOARD WAKE VORTEX AVOIDANCE SYSTEM"

NASA-CR-187521, April 1987, Continuum Dynamics, Inc., Princeton, NJ

It was determined that an onboard vortex wake detection system using existing, proven instrumentation is technically feasible. This system might be incorporated into existing onboard systems such as a wind shear detection system, and might provide the pilot with the location of a vortex wake, as well as an evasive maneuver so that the landing separations may be reduced. It is suggested that this system might be introduced into our nation's commuter aircraft fleet and major air carrier fleet and permit a reduction of current landing separation standards, thereby reducing takeoff and departure delays.

Bilanin, A. J., Teske, M. E. and Curtiss, Jr., H. C.

"ONBOARD WAKE VORTEX AVOIDANCE: INSTRUMENTATION TO QUANTIFY VORTEX WAKE HAZARD"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 55-1 - 55-27

An onboard vortex wake detection system using existing proven instrumentation such as a combination of accelerometers and angle of attack vanes may be technically feasible. This system might be incorporated into existing onboard systems (such as wind-shear detection systems) and might provide the pilot with the location of the vortex wake as well as a suggested evasive maneuver. This system, if implemented, might permit a reduction of current landing separation, thereby reducing takeoff and departure delays. This instrumentation may also have a short-term use in quantifying the magnitude of upset resulting from an aircraft encountering a vortex wake. Several onboard wake detection systems are discussed and limitations are identified. Their use as a wake hazard detector will also be discussed.

Bilanin, A. J., Teske, M. E. and Hirsh, J. E.

"THE ROLE OF ATMOSPHERIC SHEAR, TURBULENCE, AND A GROUND PLANE ON THE DISSIPATION OF AIRCRAFT VORTEX WAKES"

AIAA Paper 1978-0110, January 1978, Huntsville, AL.

Enhanced dispersion of two-dimensional trailed vortex pairs within simplified neutral atmospheric backgrounds is studied numerically for three conditions: when the pair is imbedded in a constant turbulent bath (constant dissipation); when the pair is subjected to a mean cross-wind shear; and when the pair is near the ground. Turbulent transport is modeled using second-order closure turbulent transport theory. The turbulent background fields are constructed using a super equilibrium approximation. The computed results allow several general conclusions to be drawn with regard to the reduction in circulation of the vortex pair and the rolling moment induced on a following aircraft: (1) the rate of decay of a vortex pair increases with increasing background dissipation rate; (2) cross-wind shear disperses the vortex whose vorticity is opposite to the background; and (3) the proximity of a ground plane reduces the hazard of the pair by scrubbing. The phenomenon of vortex bounce is explained in terms of secondary vorticity produced at the ground plane. Qualitative comparisons are made with available experimental data, and inferences of these results upon the persistence of aircraft trailing vortices are discussed.

Bilanin, A. J., Teske, M. E. and Hirsh, J. E.

"NEUTRAL ATMOSPHERIC EFFECTS IN THE DISSIPATION OF AIRCRAFT VORTEX WAKES"

AIAA Journal, Vol. 16, No. 9, September 1978, pp. 956-961

Enhanced dispersion of two-dimensional trailed vortex pairs within simplified neutral atmospheric backgrounds is studied numerically for three conditions: when the pair is imbedded in a constant turbulent bath (constant dissipation); when the pair is subjected to a mean crosswind shear; and when the pair is near the ground. Turbulent transport is modeled using second-order closure turbulent transport theory. The computed results allow several general conclusions to be drawn with regard to the reduction in circulation of the vortex pair and the rolling moment induced on a following aircraft: 1) the rate of decay of a vortex pair increases with increasing background dissipation rate; 2) crosswind shear disperses the vortex whose vorticity is opposite to the background; and 3) the proximity of a ground plane reduces the hazard of the pair by scrubbing. The phenomenon of vortex bounce is explained in terms of secondary vorticity produced at the ground plane. Qualitative comparisons are made with available experimental data, and inferences of these results upon the persistence of aircraft trailing vortices are discussed.

Bilanin, A. J., Teske, M. E. and Hirsh, J. E.

"DEINTENSIFICATION AS A CONSEQUENCE OF VORTEX BREAKDOWN"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 283-296.

The physical mechanisms underlying the phenomenon of vortex breakdown have been the subject of speculation for nearly 20 years. What has become clear from numerous observations of the phenomenon on aircraft trailing vortices is that breakdown can be violently turbulent. This conclusion is drawn from the observation of smoke in the center of the vortex being dispersed with the passage of

breakdown along the vortex. The question that has been asked repeatedly by those concerned with the vortex wake hazard is: Does the vortex breakdown phenomenon provide a mechanism of sufficient magnitude to be of aid in lessening the hazard of an aircraft vortex wake? The work reported herein is an attempt to answer this question. Since the vortex breakdown phenomenon is decidedly nonlinear and from observation, violently turbulent, a numerical approach has been undertaken to define the breakdown flow field. Donaldson's second-order closure turbulent transport model has been coded in circular cylindrical coordinates. The result is an axisymmetric elliptic code in the radial and axial coordinates with time as the marching direction. The code has the capability of computing dispersal of a passive tracer.

Bilanin, A. J., Teske, M. E. and Williamson, G. G.

"VORTEX INTERACTIONS AND DECAY IN AIRCRAFT WAKES"

AIAA Journal, Vol. 15, No. 2, February 1977, pp. 250-260

The dynamic interactions of aircraft wake vortices are investigated using both inviscid and viscous models. The phenomenon of vortex merging resulting in the rapid aging of a vortex wake is examined in detail. It is shown that the redistribution of vorticity from convection and diffusion during merging is a mechanism effective in reducing the hazard of a wake. Inviscid computations show that the merging phenomenon may be sensitive to small changes in spanwise load distribution and that the fuselage vortex shed from the wing-fuselage junction can play a significant role in promoting merging of wing tip and flap vortices. Vortex wake merging computations using a second-order closure model of turbulent transport indicate that a low hazard wake occurs when the generating aircraft trails flap and wing tip vortices of the same strength and sign. This optimum is achieved when the flap vortex is located outboard approximately 40% of the distance to the tip vortex.

Bilanin, A. J., Teske, M. E., Donaldson, C. duP. and Snedeker, R. S.

"VISCOUS EFFECTS IN AIRCRAFT TRAILING VORTICES"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 61-128

The mechanism of merging of like-signed aircraft vortices leads to a rapid redistribution of trailed vorticity in a wake through both convective and turbulent processes. Merging is investigated experimentally in a small wind tunnel and analytically using a code which computes turbulent transport using a second-order closure turbulent model. Computations are reported which demonstrate the merging phenomenon, and comparisons are made with experimental results. The usefulness of point vortex computations in predicting merging is explored. Limited computations have shown that jet exhaust does not appreciably alter the merging phenomenon. The effect of ambient atmospheric turbulence on the aging of an aircraft wake is investigated at constant turbulent dissipation rate. It is shown that under stable atmospheric conditions, when atmospheric macroscales are less than or equal to the vortex spacing, misleading results may be obtained. This conclusion cautions against using one parameter to characterize the ability of the atmosphere to dissipate aircraft wake vortices.

Bilanin, A. J., Teske, M. E., Donaldson, C. duP. and Williamson, G. G.

"VORTEX INTERACTIONS AND DECAY IN AIRCRAFT WAKES"

NASA CR-2870, September 1977, Aeronautical Research Assoc. of Princeton, Princeton, NJ

The dynamic interaction of aircraft wake vortices was investigated using both inviscid and viscous models. For the viscous model, a computer code was developed using a second-order closure model of turbulent transport. The phenomenon of vortex merging which results in the rapid aging of a vortex wake was examined in detail. It was shown that the redistribution of vorticity during merging results from both convective and diffusive mechanisms.

Bilbro, J. W., Craig, G. D., George, R. W., Jeffreys, H. B., Marrero, P. J., Weaver, E. A., Krause, M. C., Dunn, T. L., DiMarzio, C. A., Harris, C. E., Sonnenschein, C. M. and Toomey, D. W.

"LASER DOPPLER VORTEX MEASUREMENTS AT JOHN F. KENNEDY INTERNATIONAL AIRPORT"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 81-93

Marshall Space Flight Center in cooperation with the Federal Aviation Administration has developed a Scanning Laser-Doppler Velocimeter System which has been used to detect, track, and measure the velocity flow fields of wake vortices of aircraft landing at John F. Kennedy International Airport. The tests were performed with the cooperation of the Transportation Systems Center and the National Aviation Facilities Experiment Center, and resulted in detailed velocity and track data on the vortices generated by over 1600 landings of 13 different aircraft types. The paper describes the overall operation and performance of the system as well as the operation of the individual components. It discusses the data-handling capabilities of the system and the algorithms used in processing the laser-Doppler data, both in real time and in post analysis. Selected runs are examined for the spectral characteristics of vortices, their transport, velocity flow fields, and circulation. A summary of the results and a description of the Kennedy tests are also provided.

Bilbro, J. W., Jeffreys, H. B., Weaver, E. A., Huffaker, R. M., Craig, G. D., George, R. W. and Marrero, P. J.

"LASER DOPPLER VELOCIMETER WAKE VORTEX TESTS"

FAA-RD-76-11, March 1976, NASA Marshall Space Flight Center, Huntsville, AL

A scanning laser Doppler velocimeter (SLDV) was installed at John F. Kennedy (JFK) International Airport and was operated for six months collecting data on vortices generated by landing aircraft. A description of the SLDV system, a summary of the JFK test operations, an analysis of selected portions of the data, and recommendations for improvements to the SLDV are presented. The vortex information, including track and velocity data, on over 1,600 aircraft landings is contained in the appendices.

Bilbro, J., Fichtl, G., Fitzjarrald, D., Krause, M. and Lee, R.

"AIRBORNE DOPPLER LIDAR WIND FIELD MEASUREMENTS"

Bulletin American Meteorological Society, Vol. 65, No. 4, April 1984, pp. 348-359.

A coherent Doppler lidar has been used in an aircraft to measure the 2-dimensional wind field in several different atmospheric situations. The lidar, a pulsed CO₂ system, was installed in the NASA Convair 990, Galilao II, and flown in a summer field program that included flights in California, in Oklahoma at the National Severe Storms Laboratory, and in Montana at the Cooperative Convective Precipitation Experiment (CCOPE). This paper provides a brief description of the instrumentation and summarizes the research flights. Examples of some of the results are given along with plans for future use of the lidar.

Billant, P. and Chomaz, J.-M.

"EXPERIMENTAL EVIDENCE FOR A NEW INSTABILITY OF A VERTICAL COLUMNAR VORTEX PAIR IN A STRONGLY STRATIFIED FIELD"

J. Fluid Mech., Vol. 418, 2000, pp. 167-188

This paper shows that a long vertical columnar vortex pair created by a double flap apparatus in a strongly stratified fluid is subjected to an instability distinct from the Crow and short-wavelength instabilities known to occur in homogeneous fluid. This new instability, which we name zigzag instability, is antisymmetric with respect to the plane separating the vortices. It is characterized by a vertically modulated twisting and bending of the whole vortex pair with almost no change of the dipole's cross-sectional structure. No saturation is observed and, ultimately, the vortex pair is sliced into thin horizontal layers of independent pancake dipoles. It is tentatively argued that this new type of instability may explain the layering widely observed in stratified turbulent flows.

Billant, P., Brancher, P. and Chomaz, J.-M.

"THREE-DIMENSIONAL STABILITY OF A VORTEX PAIR"

Physics of Fluids, Vol. 11, No. 8, August 1999, pp. 2069-2077

This paper investigates the three-dimensional stability of the Lamb-Chaplygin vortex pair. Short-wavelength instabilities, both symmetric and antisymmetric, are found. The antisymmetric mode possesses the largest growth rate and is indeed the one reported in a recent experimental study [J. Fluid Mech. 360, 85 (1998)]. The growth rates, wave numbers of maximum amplification, and spatial eigenmodes of these short-wavelength instabilities are in good agreement with the predictions from elliptic instability theory. A long-wavelength symmetric instability similar to the Crow instability of a pair of vortex filaments is also recovered. Oscillatory bulging instabilities, both symmetric and antisymmetric, are identified albeit their growth rates are lower than for the short-wavelength

instabilities. Their behavior and eigenmodes resemble those of the oscillatory bulging instability occurring in the mixing layer.

Billant, P., Chomaz, J. M., Delbende, I., Loiseleux, T., Huerre, P., Olendraru, C. and Sellier, A.

"INSTABILITIES AND VORTEX BREAKDOWN IN SWIRLING JETS AND WAKES"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

The objective of the presentation is two-fold: First, we report on recent results in the theoretical and numerical study of instabilities in swirling jets and wakes, particular attention being given to the determination of the absolute/convective nature of the instability. Secondly, we present a detailed experimental investigation of the onset of vortex breakdown in swirling jets.

Billant, P., Dritschel, D. G. and Chomaz, J.-M.

"BENDING AND TWISTING INSTABILITIES OF COLUMNAR ELLIPTICAL VORTICES IN A ROTATING STRONGLY STRATIFIED FLUID"

J. Fluid Mech., Vol. 561, 2006, pp. 73-102

In this paper, we investigate the three-dimensional stability of the Moore-Saffman elliptical vortex in a rotating stratified fluid. By means of an asymptotic analysis for long vertical wavelength perturbations and small Froude number, we study the effects of Rossby number, external strain, and ellipticity of the vortex on the stability of azimuthal modes $m = 1$ (corresponding to a bending instability) and $m = 2$ (corresponding to a twisting instability). In the case of a quasi-geostrophic fluid (small Rossby number), the asymptotic results are in striking agreement with previous numerical stability analyses even for vertical wavelengths of order one. For arbitrary Rossby number, the key finding is that the Rossby number has no effect on the domains of long-wavelength instability of these two modes: the two-dimensional or three-dimensional nature of the instabilities is controlled only by the background strain rate and by the rotation rate of the principal axes of the elliptical vortex relative to the rotating frame of reference. The present results for the azimuthal mode $m = 1$ suggest that the vortex-bending instabilities observed previously in quasi-geostrophic fluids (tall-column instability) and in strongly stratified fluids (zigzag instability) are fundamentally related.

Binetti, P., Ariyur, K. B., Krstic, M. and Bernelli, F.

"CONTROL OF FORMATION FLIGHT VIA EXTREMUM SEEKING"

Proceedings of the American Control Conference, May 2002, Anchorage, AK, pp. 2848-2853.

We present a comprehensive design procedure based on extremum seeking for minimum power demand formation flight, the first with performance guarantees. The procedure involves the design of a new wake robust formation hold autopilot, and transformation of the closed loop aircraft dynamics to a form in which a newly available rigorous design procedure for extremum seeking is applicable. We

apply the design procedure on a formation of Lockheed C-5s, extending the use of maximum performance formation flight to large transports. Using available experimental wake data of the C-5, we develop a model of the aircraft in the wake that models aerodynamic interference as feedback nonlinearities. Thus, our work is also the first to attain stable extremum seeking for a plant with nonlinear feedback. Optimal formation flight is attained by online minimization of an easily measurable objective, the pitch angle of the wingman.

Bingol, F.

"ADAPTING A DOPPLER LASER ANEMOMETER TO WIND ENERGY"

MS Thesis, March 2005, Technical University of Denmark, Riso, Denmark.

The Kyoto Protocol which proposes to cut greenhouse gas emissions has been developed by many countries in the world and finally signed in 2005. EU countries in particular are already being urged to raise the proportion of renewable energy, including wind energy, in their total energy production. The EU Directive on Renewable Energy, which took effect in October 2001, sets goals that the renewal energy share of electricity generation from 11 percent in 2001 to 22 percent by 2010. Most of the challenges in the wind turbine technology have been passed and turbines have become one of the leading technologies in the renewable energy business. There was a lot to do, but it did change the way of looking to the energy for mankind and this is a breakthrough in our energy history. Everybody is interested in even better designed and more efficient wind turbines. Customers want wind turbines, which work with the same performance in different surroundings and working conditions. This is a big challenge and there is a long way to go, but the development process has been started. New concepts need new tools to analyze the wind, the effect of the wind on the wind turbine and the effect of the wind turbine on the wind. Currently there are trusted tools like cup and vane anemometers measuring the wind speed and direction for the cases listed, but there are also new ideas. This thesis project is based on one of them, a remote wind-sensing tool, ZephIR. It is a Laser Doppler Anemometer prototype by QinetiQ from United Kingdom. The main goal of the project is to adapt the ZephIR to further uses within wind energy. Adaptation process includes speed up in the measurement software and a new way of using ZephIR for measuring the wake behind a wind turbine. Project is an experimental study. Results show that a six-fold speed up in the software is possible, and wake effect can be examined. This project has opened many new ways of investigating, suitable for a PhD project. For example, testing of a wake model with real data.

Bir, G. S., Chopra, I. and Kim, K.-C.

"HELICOPTER RESPONSE TO AN AIRPLANE'S VORTEX WAKE"

12th DGLR, European Rotorcraft Forum, Garmisch-Partenkirchen, West Germany, September 1986

An analytical formulation is developed for studying the rotor-fuselage system response to an airplane's trailing vortex field. The blades are modeled as elastic beams undergoing flap bending, lag bending and torsional deflections. The fuselage is modelled as a rigid body with five degrees of

freedom: longitudinal, lateral, vertical, roll and pitch. Quasi-steady strip theory is used to obtain aerodynamic forces, and a dynamic inflow model is used to include the wake-induced unsteady effect. Dynamic stall and reverse flow effects are also included. The coupled rotor-fuselage equations are linearized about the vehicle trim state and the blade steady-state deflected position, and then solved by a numerical time-integration technique. Dynamic response results are determined in terms of blade deflections, blade stresses, rotor disk tilts, and hub loads and moments. Results are calculated for four cases of vortex encounters: hovering helicopter with vortex axis aligned with hub center; hovering helicopter with descending vortex at 16 ft/sec; helicopter flies along vortex axis; and helicopter flies across a two-vortex system. For the vortex model, a fresh wake of a B-747 airplane is used and the response is calculated for typical helicopters including hingeless, articulated and teetering rotors.

Birch, D. and Lee, T.

"INVESTIGATION OF THE NEAR-FIELD TIP VORTEX BEHIND AN OSCILLATING WING"

Journal of Fluid Mechanics, Vol. 544, 2005, pp. 201-241.

The near-field tip-vortex flow structure behind an oscillating NACA 0015 wing was investigated at $Re = 186000$. For attached-flow and light-stall oscillations, a small hysteretic property existed between the pitch-up and pitch-down motion, and many of the vortex flow features were found to be qualitatively like those of a static wing. For deep-stall oscillations, the wing oscillations imposed a strong discrepancy in contour shapes and magnitudes between the pitch-up and pitch-down phases of the oscillation cycle. The vortex was less organized during pitch-down (because of leading-edge-vortex-induced massive flow separation) than during pitch-up. The tangential velocity, circulation and lift-induced drag increased progressively with the airfoil incidence, and had higher magnitudes during pitch-up than during pitch-down, while varying slightly with the downstream distance. The vortex size, however, was larger during pitch-down than during pitch-up. The axial flow was always wake-like during the deep-stall oscillation cycle. The normalized circulation within the inner region of the tip vortex also exhibited a self-similar structure, like that of a static wing, and was insensitive to the reduced frequency.

Birch, D. and Lee, T.

"EFFECT OF TRAILING-EDGE FLAP ON A TIP VORTEX"

Journal of Aircraft, Vol. 42, No. 2, March-April 2005, pp. 442-447

The near-wake tip vortex flow structure behind a NACA 0015 airfoil with a trailing-edge flap was investigated. Lift-induced drag was computed based on vorticity and was compared with force-balance data. The vortex strength reached a maximum immediately behind the trailing edge and remained nearly constant up to two chord lengths downstream ($x/c = 3$). The displaced flap produced a more concentrated vortex of similar diameter and a higher induced drag compared to that of a baseline airfoil and had a larger radial gradient in circulation strength for flap angle, less than or equal to 15 deg; the vortex radius increased significantly for flap angle = 20 deg. For flap angles less than or equal to 15 deg, the axial flow velocity was jetlike with the peak values increased with the flap angle. The nearly

symmetric vortex was observed at $x/c = 2.25$ for a displaced flap while at $x/c = 1.5$ for a baseline airfoil. The strength and interaction of the secondary and main vortices along the tip were also found to increase with the flap angle, and the vortex flow (immediately downstream of the deflected flap) was dominated by the presence of multiple vortices. The normalized circulation in the inner part of the symmetric vortex exhibited a self-similar structure, insensitive to the flap angle.

Birch, D. and Lee, T.

"TIP VORTEX BEHIND A WING OSCILLATED WITH SMALL AMPLITUDE"

J. of Aircraft, Vol. 42, No. 5, September-October 2005, pp. 1200-1208.

The effect of reduced frequency on the tip vortex in the near field behind a NACA 0015 wing oscillated sinusoidally within the static-stall angle ($= 14$ deg) was investigated at $Re = 1.86 \times 10,000$. The nearly symmetric vortex was observed at 0.5 to 1.5 chords downstream of the trailing edge similar to the case of a stationary wing. The oscillating wing produced a less concentrated vortex of similar diameter and had a larger radial gradient in circulation strength, compared to that of a stationary wing, for reduced frequency less than about 0.1. The axial-flow velocity was always wake-like, with its minimum value increasing with the reduced frequency. The peak value of the vorticity and the vortex strength and the lift-induced drag were higher during pitch-down than during pitch-up. The normalized circulation in the inner part of the axisymmetric vortex also exhibited a self-similar structure, which was insensitive to the reduced frequency. The induced drag increased with the reduced frequency.

Birch, D. and Lee, T.

"TIP VORTEX BEHIND A WING UNDERGOING DEEP-STALL OSCILLATION"

AIAA Journal, Vol. 43, No. 10, October 2005, pp. 2081-2092

The flow structure of a tip vortex in the near field of a NACA 0015 wing with an effective aspect ratio of 5.04 undergoing a deep-stall oscillation with $\alpha(t) = 18 \text{ deg} + 6 \text{ deg} \sin \omega t$ at $Re = 1.86 \times 10,000$ was investigated. The wing oscillation imposed a strong discrepancy in contour shapes and magnitudes between the pitch-up and pitch-down phases of the oscillation cycle. The vortex was more organized and nearly axisymmetric for $x/c > 0.5$ during pitch-up than during pitch-down. The peak tangential velocity and vorticity and the strength and size of the vortex increased with $\alpha(t)$, except in the vicinity of a max, and had higher values during pitch-up than during pitch-down. The axial flow was always wake like and the velocity deficit decreased with $\alpha(t)$, while exhibiting a sharp increase and decrease on the upstroke and downstroke in the vicinity of a max, respectively. The tangential velocity decreased slightly with the downstream distance. The vortex size increased rather significantly with x/c during pitch-down while remaining virtually unchanged during pitch-up. The inner region of the vortex exhibited a self-similar structure, similar to that of a stationary wing. The induced drag increased with $\alpha(t)$ and had a local maximum at 20 deg during pitch-up.

Birch, D. M.

"SELF-SIMILARITY OF TRAILING VORTICES"

Physics of Fluids, Vol. 24, 2012, pp. 025105-1 - 025105-11.

Trailing vortices have been repeatedly shown to exhibit a remarkably robust self-similarity independent of the Reynolds number and upstream boundary conditions. The collapse of the inner-scaled circulation profiles of a trailing vortex has even been previously demonstrated for the cases of highly unsteady and turbulent vortex systems, as well as for vortices which were incompletely developed. A number of factors which contribute to and may artificially promote this self-similarity are discussed. It is shown that the amplitude of vortex 'wandering' (or the random modulations in the vortex trajectory) observed in some experimental measurements are of sufficient amplitude to cause any arbitrary finite and axisymmetric flow structure to collapse with an idealized trailing vortex when scaled on inner parameters. It is further shown that, for the case of an incompletely developed wing-tip vortex, similarity in the outer core region may be an artifact of the rate of roll-up of the vortex sheet. Great care must, therefore, be taken when interpreting experimental measurements of vortex flows.

Birch, D. M. and Martin, N.

"TRACER PARTICLE MOMENTUM EFFECTS IN VORTEX FLOWS"

Journal of Fluid Mechanics, Vol. 723, 2013, pp. 665-691.

The measurement of vortex flows with particle-image velocimetry (PIV) is particularly susceptible to error arising from the finite mass of the tracer particles, owing to the high velocities and accelerations typically experienced. A classical model of Stokes-flow particle transport is adopted, and an approximate solution for the case of particle transport within an axisymmetric, quasi-two-dimensional Batchelor q-vortex is presented. A generalized expression for the maximum particle tracking error is proposed for each of the velocity components, and the importance of finite particle size distributions is discussed. The results indicate that the tangential velocity component is significantly less sensitive to tracking error than the radial component, and that the conventional particle selection criterion (based on the particle Stokes number) may result in either over- or under-sized particles for a specific allowable error bound. Results were demonstrated by means of PIV measurements carried out in air and water using particles with very different properties.

Birch, D., Lee, T., Mokhtarian, F. and Kafyeke, F.

"STRUCTURE AND INDUCED DRAG OF A TIP VORTEX"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1138-1145

The three-dimensional flow structure of a tip vortex in the near wake of both a rectangular, square-tipped NACA 0015 airfoil and a high-lift cambered airfoil was investigated by using a seven-hole pressure probe at $Re = 2.01 \times 100,000$. Lift-induced drag was computed based on vorticity and was compared with force-balance data. For both the airfoils tested, the vortex strength reached a

maximum immediately behind the trailing edge and remained nearly constant up to two chord lengths downstream. As the airfoil incidence increased, the increase in the lift force resulted in a basically linear increase in the vortex strength and the peak values of the tangential velocity and vorticity, whereas the vortex radius did not appear to have a clear dependence on the vortex strength. Depending on the airfoil incidence, the core axial velocity could be wake-like or jet-like. The normalized circulation within the inner region of the nearly axisymmetric tip vortex exhibited a universal, or self-similar, structure. The NACA 0015 airfoil, however, possessed smaller tangential velocities but similar vortex core diameters compared to those of a cambered airfoil.

Birch, D., Lee, T., Mokhtarian, F. and Kafyeke, F.

"ROLLUP AND NEAR-FIELD BEHAVIOR OF A TIP VORTEX"

Journal of Aircraft, Vol. 40, No. 3, 2003, pp. 603-607

The formation and growth of a tip vortex in the tip and near-field regions of a single-element rectangular high-lift wing were investigated for Reynolds numbers up to 325000. The tip region was dominated by multiple secondary vortex structures. The rollup was almost complete at the trailing edge. The strength of the vortex remained nearly constant up to 1.5 chords downstream of the trailing edge. The core radius and strength and the maximum tangential and core axial velocities of the tip vortex significantly increased with the angle of attack. Also, depending on the angle of attack, the axial velocity in the core could be directed either toward the wing or away from it, that is, of wakelike or jetlike patterns.

Bird, J. D.

"TUFT-GRID SURVEYS AT LOW SPEEDS FOR DELTA WINGS"

NASA TN D-5045, February 1969, Langley Research Center, Hampton, VA.

Tuft-grid surveys were made along the chord and in the near wake of 60-degree, 75-degree, 82.5-degree, and 86.5-degree delta wings at low speeds in the Langley stability tunnel to show the nature of the flow in the vicinity of such wing planforms. The results are presented without a detailed discussion in that the photographs of the flow patterns are felt to be largely self-explanatory. An unusual wake pattern which gave evidence of three asymmetrically arranged trailing vortices was obtained for the 86.5-degree delta wing at an angle of attack of 25 degrees and zero sideslip.

Bird, J. D.

"VISUALIZATION OF FLOW FIELDS BY USE OF A TUFT GRID TECHNIQUE"

Journal of the Aeronautical Sciences, July 1952, New York, NY, pp.481-485.

A technique for obtaining a physical picture of the flow field behind a wing, combination of wings, or other airplane components is described wherein the action of a great number of tufts of uniform

length, attached to a wire grid, are photographed from far downstream. The procedure yields, with a minimum of labor, an approximate vector plot of the flow field in a plane normal to the air stream. An examination of the data obtained from an application of this tuft grid technique to the study of the flow fields behind several low aspect ratio rectangular and delta wing arrangements indicates that analyses of such factors as trailing vortex strength and location and approximate downwash and sidewash angles over a large area around lifting surfaces and other aerodynamic forms may be satisfactorily conducted by this technique.

Bird, J. D. and Riley, D. R.

"SOME EXPERIMENTS ON VISUALIZATION OF FLOW FIELDS BEHIND LOW ASPECT RATIO WINGS BY MEANS OF A TUFT GRID"

NACA TN-2674, May 1952, Langley Aeronautical Lab., Langley Field, VA

A technique for obtaining a physical picture of the flow behind lifting surfaces is described wherein the action of a large number of tufts of uniform length attached to a wire grid are photographed from far downstream. The procedure yields, with a minimum of labor, an approximate vector plot of the flow field in a plane normal to the air stream. The flow fields behind a rectangular wing and several triangular wings were investigated through the angle-of-attack range. The effects of tip-control deflection, sideslip, and oscillation in sideslip on the flow field behind a 60-degree triangular wing were also determined.

Bisgood, P. L.

"IN-FLIGHT STUDIES OF VORTEX WAKES, 1970-73"

TM AERO-1554, November 1973, Royal Aircraft Establishment, Farnborough, England.

In-flight studies of vortex wakes made in the UK during 1970-73 are described together with some discussion of the results, so far as the latter are available.

Bisgood, P. L., Maltby, R. L. and Dee, F. W.

"SOME WORK AT THE ROYAL AIRCRAFT ESTABLISHMENT ON THE BEHAVIOR OF VORTEX WAKES"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 171-206

The paper reviews the work done at the Royal Aircraft Establishment on the behavior of vortex wakes. Measurements of the development of wakes behind straight and swept wings are described. The results of observations on the formation of loops in a vortex wake, on the behavior of the wakes close to the ground, and on the development of the wake from a slender wing are given in some detail.

Bizinos, N. and Redelinghuys, C.

"TENTATIVE STUDY OF PASSENGER COMFORT DURING FORMATION FLIGHT WITHIN ATMOSPHERIC TURBULENCE"

Journal of Aircraft, Vol. 50, No. 3, May-June 2013, pp. 886-900.

Formation flight is currently being investigated to reduce drag and improve fuel efficiency in commercial aviation. To approximate passenger impact in formation flight, a simple aerodynamic model for two aircraft in formation was developed. The wing trailing vortices were assumed to shift in an ideal fashion within atmospheric turbulence resulting in aerodynamic disturbance loads acting on the trailing aircraft. As the sensitivity of the human body to vibration is frequency dependent, a spectral representation of atmospheric turbulence was incorporated. Monte Carlo simulations were done for various levels of turbulence intensity. The predicted acceleration responses of the trailing aircraft were used to determine the passenger comfort levels by applying the criteria of standard 2631-1 from the International Organization for Standardization and comparing with comfort levels experienced in an aircraft flying in isolation in the same turbulent atmosphere. A significant increase in discomfort was predicted for the lateral separations corresponding to the location for optimum drag benefit. Seating locations forward and inboard (closer to the lead aircraft) of the mass center showed the greatest increase in discomfort..

Blackmore, D. and Champanerkar, J.

"PERIODIC AND QUASIPERIODIC MOTION OF POINT VORTICES"

In Vortex Dominated Flows, edited by D. Blackmore, E. Krause and C. Tung, 2005, World Scientific, New Jersey, Chapter 2, pp. 21-42.

Several generalizations and recent extensions of the Poincare-Birkhoff fixed point theorems are presented, along with applications to some problems in vortex dynamics. The problem of four-or-more point vortices in a plane is analyzed in considerable detail for the case where all the vortex strengths have the same sign. This is accomplished using a combination of KAM theory and a recent version of the Poincare-Birkhoff fixed point theorem. For example, it is proved that if the diameter of the initial system of vortices is sufficiently small, there exists an ample set of starting configurations that produce dynamics exhibiting quasiperiodic flows on invariant KAM tori, and periodic orbits of arbitrarily large period near these tori. It is also shown that analogous dynamical behavior occurs for configurations of any finite number of point vortices in a half-plane.

Blackmore, D. and Knio, O.

"A HAMILTONIAN APPROACH TO VORTEX BREAKDOWN"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

The flow of fluid particles in an ideal fluid induced by the motion of a pair of coaxial vortex rings in a swirling flow is studied in the context of Hamiltonian dynamics. By assuming that the axisymmetric

flow induced by the pair of coaxial vortex rings (kinematics) is modeled by a desingularized version of the Biot-Savart law, one obtains a stream function for the velocity field that is tantamount to a time-varying Hamiltonian function for the equations of motion. A new coordinate system moving with the center of vorticity of the rings is introduced and the Hamiltonian function is determined by solving the completely (Liouville-Arnold) integrable Hamiltonian equations for the ring motion (dynamics). This leads to a decomposition of the Hamiltonian for the fluid kinematics into a completely integrable term plus a nonintegrable part whose size can be controlled by making the initial distance between the rings sufficiently small, depending on the ambient swirl. Whence we obtain a Poincare map for the flow with respect to any fixed meridional half-plane that is a twist map. As the initial separation of the rings is increased, the invariant tori tend to break up and the fluid trajectories become more irregular until a point is reached where transverse homoclinic periodic points appear and Smale horseshoe chaos ensues. Thus, the two-ring model enables one to prove the existence of a wide range of regular and chaotic dynamical structures, depending on natural system parameters, that are remarkably consistent with those found in several experimental and numerical studies of axisymmetric bubble-type (B-type) vortex breakdown.

Blackmore, P. A.

"THE EFFECTS OF AIRCRAFT TRAILING VORTICES ON HOUSE ROOFS"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 52, No. 4, 1994, pp. 155-170

This paper describes work carried out by the Building Research Establishment to investigate the phenomenon of aircraft trailing vortices and their effect on the roofs of domestic dwellings. As part of this investigation the roof of a house close to runway 27R at Heathrow Airport was instrumented to detect vortices. Measurements of pressure and velocity were carried out for nearly 3000 h during a 12-month period in 1991/92. During this period 399 vortex strikes were detected on the test house giving an average strike rate of 1.5/day. Most of these strikes produced pressures within the range plus or minus 150 Pa. On 6 occasions suctions exceeded - 500 Pa with a maximum suction of - 1190 Pa. Over 70% of all vortex strikes occurred when the ambient mean wind speed was below 5 m/s. Peak instantaneous tangential velocities of up to 40 m/s were recorded at the anemometer location.

Blackmore, P. A. and Redfearn, D.

"AIRCRAFT TRAILING VORTICES AND THEIR EFFECT ON ROOFS"

Journal of Meteorology, Vol. 18, No. 181, September 1993, pp. 229-237

This paper describes work carried out by the Building Research Establishment to investigate the phenomenon of aircraft trailing vortices and their effects on roofs. Measurements of vortex pressure and velocity on the roof of a house close to the end of runway 27R at Heathrow Airport were made during a 12-month period in 1991/92. During this period 399 vortex strikes were detected giving an approximate strike rate of 1.5/day. The minimum vortex pressure measured on the roof was -1190 Pa and the maximum vortex tangential velocity measured at the anemometer was 40 m/s.

Blackmore, T., Batten, W. M. J., Muller, G. U. and Bahaj, A. S.

"INFLUENCE OF TURBULENCE ON THE DRAG OF SOLID DISCS AND TURBINE SIMULATORS IN A WATER CURRENT"

Experimental Fluids, Vol. 55, 2014, pp. 1637-1 to 1637-10.

Laboratory experiments have been used to investigate the effects of turbulence on the drag of both solid discs and porous disc turbine simulators. These discs were introduced to turbulent flows, in a gravity-fed water flume, with various levels of turbulence intensity and integral length scales. The turbulence was generated using three different grid configurations, which produced intensities and scales comparable with previous wind tunnel studies. The drag measurements were taken with discs of two different diameters and porosities with and without the upstream grids. The experimental results have demonstrated that the drag coefficients, of all discs tested, are significantly dependent on both the turbulence intensity and integral length scale. For small integral length scales, relative to the disc, the drag coefficients converged for turbulence intensities greater than 13 percent, with an increase of around 20 percent in drag coefficient over the low-intensity case. Experiments with turbulence intensities of 10 percent demonstrated minimum drag coefficients when the integral length scale-to-disc diameter ratio was around 50 percent. Significant variations in the drag coefficient of circular bluff bodies are therefore expected when operating in turbulent flows with different characteristics.

Blackwelder, R. F. and Eckelmann, H.

"STREAMWISE VORTICES ASSOCIATED WITH THE BURSTING PHENOMENON"

Journal of Fluid Mechanics, Vol. 94, part 3, 1979, pp. 577-594.

The streamwise and spanwise velocity components and the gradients of these components normal to the wall were examined by using hot-film sensors and flush-mounted wall elements to study the vortex structures associated with the bursting phenomenon. Quadrant probability analysis and conditional sampling techniques indicated that pairs of counter-rotating streamwise vortices occur frequently in the wall region of a bounded turbulent shear flow. A streamwise momentum defect occurred between the vortices as low-speed fluid was 'pumped' away from the wall by the vortex pair. The defect region was long and narrow and possibly forms the low-speed streak as observed in visualization studies. The velocity defect was terminated by a strong acceleration followed by a high-speed region.

Blackwelder, R. F., Gad-el-Hak, M. and Srnsky, R.A.

"METHOD AND APPARATUS FOR CONTROLLING BOUND VORTICES IN THE VICINITY OF LIFTING SURFACES"

US Patent 4,697,769, October 1987

The lift generated by delta wings is due primarily to large vortices associated with the flow separation near the leading edge. The invention includes a perturbation device to control the separation shedding of those vortices and manipulate their frequency and pairing. This results in different growth rates of the vortices downstream of the device and thus the lift produced by the large bound vortices may be controlled. If the invention is applied to both leading edges, the total lift of the wing will be altered; if the perturbation is preferentially applied on only one side of the wing, the moment around the roll axis of the aircraft is controlled. A first embodiment uses a piston coupled to a cavity and slot to produce the desired perturbation. Alternative embodiments are described which achieve the results without moving parts.

Blaisdell, G. A. and Eshpuniyani, B.

"DNS AND LES OF A STRAINED TURBULENT AXIAL VORTEX"

Third AFOSR International Conference on Direct Numerical Simulation and Large Eddy Simulation (TAICDL), Arlington, TX, August 2001

The work presented includes direct numerical simulations (DNS) and large eddy simulations (LES) of a strained turbulent axial vortex. This effort is part of an on-going project on the DNS and LES of turbulent axial vortices with and without the effect of an external strain field. The overall project is motivated by the wake hazard problem for commercial aircraft where the wing-tip vortices behind large aircraft present a serious safety concern for the following aircraft. For progress to be made in the prediction and control of these vortices, it will be helpful to have a better understanding of how turbulence within these vortices behaves and how the turbulence affects the distribution of vorticity. Also, current turbulence models do not perform well for strongly rotating flows and the current study provides needed data for the improvement of turbulence models for such flows.

Blake, W.

"PREDICTION OF PARATROOP/WAKE VORTEX ENCOUNTERS DURING FORMATION AIRDROP"

AIAA Paper No. 1996-3387, Reston, VA, 1996

A modeling technique is described for predicting the relative locations of paratroops and trailing vortices for a formation of transport aircraft. The wake behind each vehicle is treated as a fully rolled up vortex pair with empirical relations used for the vortex decay. The technique is applied to two and six aircraft formations, with the objective being to maximize the distance between the vortices and paratroops, subject to numerous operational constraints. Nineteen sorties were flown using the formations developed. A total of 286 mannequins and 299 live troops were dropped with no paratroop/wake vortex interactions observed.

Blake, W. B.

"AN AERODYNAMIC MODEL FOR SIMULATION OF CLOSE FORMATION FLIGHT"

AIAA Paper No. 2000-4304, Denver, CO, August 2000.

A mathematical representation of the aerodynamics for simulation of many vehicles in close formation flight is presented. Aerodynamic coupling effects between the aircraft due to wake interference are included. A combination of wind tunnel results and vortex lattice analysis is used to significantly reduce the number of state variables included in the aerodynamic coupling terms. Computational results are presented for two tailless aircraft at a wide variety of relative locations.

Blake, W. B.

"DEVELOPMENT OF THE C-17 FORMATION AIRDROP ELEMENT GEOMETRY"

Journal of Aircraft, Vol. 35, No. 2, March-April 1998, pp. 175-182

The analysis and tests that established a three-ship C-17 element geometry suitable for formation airdrop operations at night are discussed. The objective is to avoid jumpers encountering vortices generated by aircraft upstream. Candidate formation geometries were judged using a vortex tracking code that estimated the closest lateral proximity between a vortex and a jumper for a given wind condition. The initial formation geometry underwent two changes during the test because of the introduction of tolerance boxes for aircraft position and vortex encounters that occurred during mannequin trials. An echelon geometry 6000 ft long and 1500 ft wide was ultimately adopted. In 101 passes over the drop zone, 1349 mannequins and 1251 personnel were dropped from this formation geometry without a vortex encounter.

Blake, W. B. and Gingras, D. R.

"COMPARISON OF PREDICTED AND MEASURED FORMATION FLIGHT INTERFERENCE EFFECTS"

Journal of Aircraft, Vol. 41, No. 2, March-April 2004, pp. 201-207

Results from a wind-tunnel test of two delta-wing aircraft in close proximity are presented and compared with predictions from a vortex lattice method. Large changes in lift, pitching moment, and rolling moment are found on the trail aircraft as it moves laterally relative to the lead aircraft. The magnitude of these changes is reduced as the trail aircraft moves vertically with respect to the lead aircraft. Lift-to-drag ratio of the trail aircraft is increased when the wing tips are slightly overlapped. Wake-induced lift is overpredicted slightly when the aircraft overlap in the spanwise direction. Wake-induced pitching and rolling moments are well predicted. A maximum induced drag reduction of 25% is measured on the trail aircraft, compared with a 40% predicted reduction. Three positional stability derivatives, change in lift and pitching moment with vertical position and change in rolling moment with lateral position, are studied. Predicted boundaries between stable and unstable regions were generally in good agreement with experimentally derived boundaries.

Blake, W. B., Dickes, E. G. and Gingras, D. R.

"UAV AERIAL REFUELING -- WIND TUNNEL RESULTS AND COMPARISON WITH ANALYTICAL PREDICTIONS"

AIAA Paper 2004-4820, August 2004, Providence, RI.

Results from a wind tunnel test of a delta wing UAV behind a KC-135R are presented and compared with predictions from a planar vortex lattice code. Both the predictions and data show wake interference effects on the UAV that vary significantly with relative lateral and vertical position, and weakly with relative longitudinal position. Predicted trends are excellent for all force and moments except for drag, and magnitudes are reasonably well predicted. The distribution of lift between the tanker wing and tail is shown to have a strong effect on the receiver aerodynamics.

Blanco-Rodriguez, F. J., Rodriguez-Garcia, J. O., Parras, L. and del Pino, C.

"OPTIMAL RESPONSE OF BATCHELOR VORTEX"

Physics of Fluids, Vol. 29, 2017, pp. 064108-1 to 064108-14.

The optimal response of the Batchlor vortex is studied by considering the time-harmonically forced problem with frequency w . High variance levels are sustained in this system under periodic forcing. The optimal response is largest when the input frequency is null in the axisymmetric case ($m=0$). In addition, the axial flow does not play a relevant part in determining the optimal response. When considering helical modes.

Bleviss, Z. O.

"THEORETICAL ANALYSIS OF LIGHT PLANE LANDING AND TAKE-OFF ACCIDENTS DUE TO ENCOUNTERING THE WAKES OF LARGE AIRPLANES"

Report SM-18647, December 1954, Douglas Aircraft Co., Santa Monica, CA

Many accidents and near accidents have been caused by light planes encountering the wakes of large airplanes during landing and take-off even though normal separation times were observed. The two typical difficulties generally reported by the pilots of the light plane were: a sudden violent roll accompanied or unaccompanied by a sudden large 'apparent' loss of lift characterized by rapid loss of altitude. A theoretical analysis of the cause of these accidents is presented in this report. It is shown that the accidents are caused by the rotational field of air associated with the rolled-up trailing vortex system from the wing of the large airplane. The suddenness of the onset of the difficulties is due to the unexpected entry of the light plane into this vortex system.

Bliss, D. B.

"NEW VORTEX DYNAMICS METHODS FOR ROTOR FREE WAKE ANALYSIS"

ARO 25747.1-EG, May 1993, Duke University, Durham, NC.

This report summarizes recent work on rotorcraft aerodynamics involving novel methods for rotor free wake calculations. A new method called Analytical/Numerical Matching (ANM) was developed. ANM is a hybrid analytical and numerical method that achieves accurate results by combining a low-resolution numerical solution with a high-resolution analytical solution. Although originally developed for vortex dynamics, ANM has proven to be of a general nature. The application of ANM to the rotor wake problem provides accurate answers with a significant reduction in computation time. The use of ANM introduces the opportunity to develop new solution strategies, including Far-Field Linearization and Periodic Inversion. These methods afford the means to obtain accurate solutions over the entire flight regime. Work involving applications of ANM has also led to a scheme that represents vortex filament dynamics by a hierarchy of nested problems of varying resolution joined by matching solutions. This approach, called ANM with Pyramiding, has reduced calculation times by more than a factor of twenty in some sample problems.

Bliss, D. B.

"THE DYNAMICS OF FLOW WITH HIGH CONCENTRATIONS OF VORTICITY"

Ph.D. Thesis, June 1973, Mass. Institute of Technology, Cambridge, MA

A general method is developed for predicting the dynamics of curved rotational vortex lines with axial flow. The vortex core size must be much smaller than both the local radius of curvature and the length scale for axial variation. The self-induced motion is characterized by the size and energy content of the rotational core, as well as the filament geometry. The presence of axial flow diminishes the self-induced motion. The Biot-Savart law can be used to find the motion of a vortex filament, if the proper cut-off distance is used. A general formula for cut-off distance, depending only on local core structure, is derived. Results for a sinusoidally perturbed vortex line are compared with the solution of the dispersion relation for a hollow core vortex to ascertain the limits of validity of the solution. The prospect of finding higher order solutions is investigated and the additional effects that can arise are identified.

Bliss, D. B.

"EFFECT OF UNSTEADY FORCING ON THE SINUSOIDAL INSTABILITY OF VORTEX WAKES"

Journal of Aircraft, Vol. 19, No. 9, September 1982, pp. 713-721

An analytical model of the vortex wake instability subject to forcing by unsteady lift fluctuations has been developed. These lift fluctuations can be caused either by variations in angle of attack or by flying through atmospheric turbulence. The effect of turbulence in the fluid itself, already studied by Crow and Bate, has been reviewed and incorporated into the analysis. A simple procedure is provided to estimate the time at which contact occurs between the two wake vortices as a function of certain characteristics of the forcing inputs. The behavior of the instability is somewhat altered by these forcing terms. In particular, it was found that contact between vortices can occur at much shorter wavelengths than predicted for the unforced case. Furthermore, in the presence of forcing, the

minimum completion time for the instability does not correspond to the wavenumber for which the amplification rate is a maximum because the length of the vortex trajectories is also an important factor. Finally, the stability boundary is extended to larger wavenumbers by the presence of forcing, and the boundary location depends on the forcing level.

Bliss, D. B. and Epstein, R. J.

"NOVEL APPROACH TO AERODYNAMIC ANALYSIS USING ANALYTICAL/NUMERICAL MATCHING"

AIAA Journal, Vol. 34, No. 11, November 1996, pp. 2225-2232.

Analytical/numerical matching (ANM) is a hybrid scheme combining a low-resolution global numerical solution with a high-resolution local solution to form a composite solution. ANM is applied to lifting surfaces in steady potential flow to calculate the aerodynamic loading and associated circulation distribution. The solution methodology utilizes overlapping smoothed doublets and local corrections to calculate the doublet strength distribution along the airfoil chord. The global low-resolution solution is calculated numerically using smoothed doublet solutions to the linear potential equation, and converges quickly. Simultaneous local corrections are done with high-resolution local analytical solutions. The global numerical solution is asymptotically matched to the local analytical solutions via a matching solution. The matching solution cancels the global solution in the near field, and cancels the local solution in the far field. The method is very robust, offering insensitivity to control-point location. ANM provides high-resolution calculations from low resolution numerics with analytical corrections, while avoiding the subtlety involving singular integral equations, and their numerical implementation. The approach provides a novel alternative treatment to lifting-surface aerodynamics.

Bliss, D. B., Teske, M. E. and Quackenbush, T. R.

"A NEW METHODOLOGY FOR FREE WAKE ANALYSIS USING CURVED VORTEX ELEMENTS"

NASA CR-3958, December 1987, Continuum Dynamics, Inc., Princeton, NJ

The Basic Curved Vortex Element (BCVE) was developed to do rotor free wake calculations. The element is based on the approximate Biot-Savart integration for a parabolic arc filament shape. A scheme called the interpolated point method was also developed to determine the curvature and orientation of these elements when placed between collocation points along the wake contour. The computer time and accuracy of the BCVE were studied extensively in relation to the performance of the simpler straight-line elements which have traditionally been used. In numerical simulations, curved elements were found to be far more accurate in predicting vortex filament flow fields, even when much larger elements were used. Although the curved element is more complex analytically, the fact that the elements can be larger leads to a net reduction in computer time while maintaining a strong accuracy advantage. As part of the accuracy study, the errors made by straight-line elements were evaluated. These errors were found to be related to deviations in position relative to the filament contour and to a failure to simulate the local curvature of the arc. Based on a local analysis, universal formulas were developed for predicting straight-line element errors. Within one element length of a vortex filament,

straight-line elements induce velocity errors of the same order as the self-induced velocity due to local curvature, an effect included in free wake analyses. The curved element method was implemented into a forward flight free wake analysis using a time stepping approach. A new far wake model was also developed which utilizes free wake information to prescribe and update the far wake shape downstream of the free wake region. Sample calculations were performed for different element sizes and advance ratios for single and multi-blade rotors. The highly distorted free wake shapes showed several common features, the most distinctive being a strong tendency toward rapid roll-up of the sides of the wake immediately downstream of the rotor. A preliminary assessment was made of the effect of element size on the downwash size at a rotor blade, with there being only small differences between elements generated by 15 deg, 30 deg, and 45 deg increments of blade rotation. In general, the curved element approach exhibited rapid convergence. As a final demonstration of capability, the free wake routine was implemented into the Boeing Vertol B-65 rotor aerodynamics program. Sample calculations were performed for a four-bladed rotor with a prescribed wake and with free wakes using different element sizes.

Bloom, A. M. and Jen, H.

"ROLL-UP OF AIRCRAFT TRAILING VORTICES USING ARTIFICIAL VISCOSITY"

Journal of Aircraft, Vol. 11, No. 11, November 1974, pp. 714-716

A study was made of the roll-up characteristics of aircraft trailing vortices applying the artificial viscosity method of Kuwahara and Takami to a number of practical aerodynamic configurations and comparing the results for the core location with existing experimental data where possible.

Bloy, A. W. and Jouma'a, M.

"TRAILING VORTEX EFFECTS ON LARGE RECEIVER AIRCRAFT"

Journal of Aircraft, Vol. 32, No. 6, November-December 1995, pp. 1198-1204

The aerodynamic forces and moments on the Hercules receiver aircraft, due to its horizontal and vertical position and bank, yaw, and pitch attitudes in the wake of the KC10 tanker aircraft, are assessed relative to the receiver's aerodynamic characteristics in free air. Large changes in lift, drag, and pitching moment are predicted near the tanker wake centerline. As the receiver is displaced sideways towards the tanker wingtip vortices it experiences large side force and yawing moment and particularly high rolling moment. The most significant term due to the receiver attitude is the rolling moment due to bank.

Bloy, A. W. and Lea, K. A.

"DIRECTIONAL STABILITY OF A LARGE RECEIVER AIRCRAFT IN AIR-TO-AIR REFUELING"

J. Aircraft, Vol. 32, No. 2, March-April 1995, pp. 453-455

Wind-tunnel data have been obtained from a receiver aircraft model tested in yaw behind a tanker aircraft model. Because of the sidewash acting on the fin below the tanker wake, the receiver aircraft experienced a significant loss of directional stability. The effect of the sidewash on the receiver fuselage was found to be relatively small. Tests with and without a fuselage on the tanker differed slightly. Similar results were obtained for the side force derivative. The theoretical results obtained using a roll-up model of the tanker wing wake and excluding fuselage effects compare favorably with the experimental data.

Bloy, A. W. and West, M. G.

"INTERFERENCE BETWEEN TANKER WING WAKE WITH ROLL-UP AND RECEIVER AIRCRAFT"

Journal of Aircraft, Vol. 31, No. 5, September-October 1994, pp. 1214-1216

A model of wing wake roll-up has been developed and applied to the problem of the lateral aerodynamic interference between tanker and receiver aircraft during air-to-air refueling. For the configuration considered, the wake roll-up gives a tip vortex strength at the receiver wing position that is 42.5% of the circulation at the tanker wing centerline. From the downwash and sidewash distributions the receiver rolling moments due to sideways and bank displacements have been calculated. Compared with the predictions from a flat vortex sheet model of the wing wake, the predictions from the wake roll-up model indicate significantly higher values of the receiver rolling moment due to sideways displacement derivative. For the configuration considered, the effect of roll-up on the receiver rolling moment due to bank derivative is negligible.

Bloy, A. W., West, M. G., Lea, K. A. and Jouma'a, M.

"LATERAL AERODYNAMIC INTERFERENCE BETWEEN TANKER AND RECEIVER IN AIR-TO-AIR REFUELING"

J. Aircraft, Vol. 30, No. 5, Sept.-Oct. 1993, pp. 705-710

Wind-tunnel data have been obtained from a tapered tanker wing and receiver aircraft model at varying vertical separation. The data are presented in derivative form and compared with theory using a flat vortex sheet model of the tanker wing wake to determine the induced angle-of-attack variation on the receiver wing, fin, and tailplane due to the tanker wing. Aerodynamic loads on the receiver are obtained by the vortex lattice method, with an allowance made for the vertical displacement of the tanker wake in the estimation of the fin side force. In the experiments, the lateral aerodynamic interference between tanker and receiver was determined by banking the tanker wing and displacing it sideways, and by yawing the receiver aircraft model. Data were obtained from open and closed test sections to assess the significant boundary interference effect and corrections estimated from the image vortex system of the tanker and receiver wings in the test section. In general, the theory compares favorably with the experimental data. The most significant terms are the rolling moments due to sideways and bank displacements. Significant side forces are produced due to sidewash on the fin from the tanker and receiver wings and, when displaced in yaw, the receiver experienced a loss in directional stability.

Bluemink, J. J., Lohse, D., Prosperetti, A. and van Wijngaarden, L.

"DRAG AND LIFT FORCES ON PARTICLES IN A ROTATING FLOW"

Journal of Fluid Mechanics, Vol. 643, 2010, pp. 1-31.

A freely rotating sphere in a solid-body rotating flow is experimentally investigated. When the sphere is buoyant, it reaches an equilibrium position from which drag and lift coefficients are determined over a wide range of particle Reynolds numbers (Re greater than or equal to 2 and less than or equal to 1060). The wake behind the sphere is visualized and appears to deflect strongly when the sphere is close to the cylinder axis. The spin rate of the sphere is recorded. In fluids with low viscosity, spin rates more than twice as large as the angular velocity of the cylinder can be observed. By comparing numerical results for a fixed but freely spinning sphere with a fixed non-spinning sphere for Re less than or equal to 200, the effect of the sphere spin on the lift coefficient is determined. The experimentally and numerically determined lift and drag coefficients and particle spin rates all show excellent agreement for Re less than or equal to 200. The combination of the experimental and numerical results allows for a parameterization of the lift and drag coefficients of a freely rotating sphere as function of the Reynolds number, the particle spin and the location of the particle with respect to the cylinder axis. Although the effect of the flow rotation on the particle spin is different in shear flow and solid-body rotating flow, the effect of spin on lift is found to be comparable for both types of flow.

Bly, E.

"EFFECTS OF REDUCED IFR ARRIVAL-ARRIVAL WAKE VORTEX SEPARATION MINIMA AND IMPROVED RUNWAY OPERATIONS SEQUENCING ON FLIGHT DELAY"

M.S. Thesis, February 2005, Mass. Institute of Technology, Cambridge, MA

Two methods to improve runway throughput are evaluated in this thesis. The first, increasing runway capacity during periods of bad weather by reducing IFR arrival-arrival wake vortex separations. The second, increasing runway efficiency in all weather conditions using event sequencing algorithms. Two algorithms were studied: a Serve-the-Longest-Queue algorithm for flight sequencing coupled with a greedy heuristic algorithm for runway assignment and a mixed integer programming optimization algorithm for simultaneous flight sequencing and runway assignment. The MIT Extensible Air Network Simulation (MEANS) was used to simulate NAS operations to determine the potential benefits in terms of delay reduction for both methods. For the case where reduced IFR arrival-arrival wake vortex separations was studied, the Airport Runway Capacity Calculator (ARCC), developed in support of this work, was used to determine the increased capacity at eleven congested US airports. Results indicate that the total delay in the National Airspace System (NAS) could have been reduced by 31.8% over the month of January, 1999 (a reduction of 243,672 minutes) representing a benefit of 116 minutes per IFR hour. For the cases where the event sequencing algorithms were studied, the algorithms were only implemented at Newark Airport (EWR) and the resulting delay values were compared to the

performance of a FIFO algorithm that is representative of existing operations. The flight delay for the Serve-the-Longest-Queue algorithm and the FIFO algorithm were similar, though relative performance depended on the airline schedule. The integer programming optimization algorithm outperformed the other two algorithms significantly reducing the average delay at EWR by 65.6% and 67.0% and the average NAS delay by 24.3% and 24.7% relative to the FIFO and Serve-the-Longest-Queue algorithms respectively.

Boatright, W. B.

"AN ANALYSIS OF PRESSURE STUDIES AND EXPERIMENTAL AND THEORETICAL DOWNWASH AND SIDEWASH BEHIND FIVE POINTED-TIP WINGS AT SUPERSONIC SPEEDS"

NACA-TR-1380, 1958, NACA Langley Aeronautical Lab., Langley Field, VA.

Flow-angle and pressure surveys behind five, thin, pointed-tip wings of varying plan form have been made at Mach numbers 1.62 and 2.41. Schlieren studies at a Mach number 1.93 for the same five plan-form wings were made to illustrate the behavior of the vortex sheet. The surveys were conducted at 1.5, 3, and 4 root chords behind three triangular wings of 50-degree, 63-degree, and 72-degree leading-edge sweep angle, and behind the 50-degree, triangular wing reversed. The flow behind a pointed-tip wing having a sweptback leading edge and a swept forward trailing edge (both 50 degrees) was also surveyed. Experiment and one of the theoretical methods are compared for the reversed triangular wing and the pointed-tip wing with the 50-degree sweptback leading edge and sweptforward trailing edge.

Boatwright, D. W.

"A STUDY OF THE INFLUENCE OF WING-TIP VORTICES ON THE TRAJECTORIES OF PARTICLES RELEASED FROM AIRCRAFT"

Journal No. 1702A, December 1968, Mississippi State Univ. Agriculture Experiment Station, State College, MS.

This report describes results of tests conducted to determine if radar reflective chaff injected at the wing tip of an aircraft would be ingested into the vortex structure and sufficiently distributed to allow velocity profiles to be measured by a Doppler radar. The results are presented in the form of flow field visualization results and an analysis of radar returns.

Boatwright, D. W.

"MEASUREMENTS OF VELOCITY COMPONENTS IN THE WAKE OF A FULL-SCALE HELICOPTER ROTOR IN HOVER"

U.S. AAMRDL TR-72033, 1972, Mississippi State Univ., State College, MS

This report presents three-component wake velocity measurements made with a split-film total vector anemometer. The measurements were made in the wake of a full-scale OH-13E helicopter rotor. The results indicated that maximum values of the induced velocity in the mean wake exceeded twice the magnitude of momentum values, and that instantaneous values of the vertical velocity component in the vicinity of the vortex trails could be as large as ten times the momentum value of induced velocity at high thrust coefficients. Velocity distributions across tip vortices revealed longitudinal components of velocity of the same order of magnitude as the rotational components. Also, tip vortex structure and dissipation characteristics were found to be like the vortices shed from fixed-wing aircraft.

Bobylev, A. V., Glushkov, N. N. and Gryazin, V. E.

"MATHEMATICAL MODEL OF INTERACTION WITH THE VORTEX WAKE FOR A SET OF GEOMETRICALLY SIMILAR AIRCRAFT"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 239-246

The paper considers interaction of five medium-class aircraft (UK classification) with a non-curved vortex generated by a B-747-type 'heavy' aircraft at its landing approach. The aerodynamic and inertia and mass characteristics of the set of aircraft were obtained from those of the Tu-154 aircraft by resizing method and similarity relations. The landing approach is executed in the automatic mode, the automatic control algorithms being simulated on the basis of the AFCS-154.

Bobylev, A. V., Kuzmin, V. P. and Yaroshevsky, V. A.

"AN ANALYSIS OF STOCHASTIC EFFECTS OF THE VORTEX WAKE ON AIRCRAFT MOTION AT AUTOMATED LANDING"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 197-208

The problem of the development of a stochastic model of the vortex wake behind an aircraft is considered together with the assessment of the probability of unfavorable influence on another aircraft performing an automated landing. The stochastic character of some atmospheric factors (gradient wind, atmospheric turbulence, and stratification) is taken into consideration. The stochastic model determines the influence of these factors on the motion of the vortices, changes in their circulation and random time of vortex breakdown due to the Crow instability. [In Russian.]

Bobylev, A. V., Kuzmin, V. P. and Yaroshevsky, V. A.

"MATHEMATICAL SIMULATION OF THE WAKE VORTICES EFFECT ON AIRCRAFT MOTION DURING AUTOMATIC LANDING"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 198-208

This paper considers the process of automatic landing of the Tu-204 medium weight class aircraft in the vortex wake behind a B-747-type heavy aircraft. The computations were aimed at determining the structure of the wake vortices mathematical model and the influence of this model elements upon the computational results overall. Besides it describes a methodology of statistical modeling for obtaining the probability of large deviations of trajectory kinematics parameters of an encountering aircraft at the touch-down moment. The methodology is based on the method of essential sample, which allows singling out realizations with one of the vortices near the landing trajectory.

Bobylev, A. V., Vyshinsky, V. V., Soudakov, G. G. and Yaroshevsky, V. A.

"AIRCRAFT VORTEX WAKE AND FLIGHT SAFETY PROBLEMS"

Journal of Aircraft, Vol. 47, No. 2, March-April 2010, pp. 663-674.

This paper presents a mathematical model of the aircraft vortex wake for evaluating the safe separation considering the wake-generating and following aircraft types and weather conditions. The solution of four major problems is contained in the model concerned, namely, the wake generator, the interaction of the following aircraft with the preceding aircraft vortex, the description of the turbulent atmosphere, and the vortex destruction. Verification of the model was made based on experimental results of wind-tunnel and flight tests. Given are calculations of the wake characteristics aft of aircraft and safe distance values in landing with various turbulent atmosphere states.

Bodini, N., Zardi, D. and Lundquist, J. K.

"THREE-DIMENSIONAL STRUCTURE OF WIND TURBINE WAKES AS MEASURED BY SCANNING LIDAR"

Atmospheric Measurement Techniques, Vol. 10, 2017, pp. 2881-2896.

The lower wind speeds and increased turbulence that are characteristic of turbine wakes have considerable consequences on large wind farms: turbines located downwind generate low power and experience increased turbulent loads. The structures of wakes and their downwind impacts are sensitive to wind speed and atmospheric variability. Wake characterization can provide important insights for turbine layout optimization in view of decreasing the cost of wind energy. The CWEX-13 field campaign, which took place between June and September 2013 in a wind farm in Iowa, was designed to explore the interaction of multiple wakes in a range of atmospheric stability conditions. Based on lidar wind measurements, we extend, present, and apply a quantitative algorithm to assess wake parameters such as the velocity deficits, the size of the wake boundaries, and the location of the wake centerlines. We focus on wakes from a row of four turbines at the leading edge of the wind farm to explore variations between wakes from the edge of the row (outer wakes) and those from turbines in the center of the row (inner wakes). Using multiple horizontal scans at different elevations, a three-dimensional structure of wakes from the row of turbines can be created. Wakes erode very quickly during unstable conditions and can in fact be detected primarily in stable conditions in the conditions

measured here. During stable conditions, important differences emerge between the wakes of inner turbines and the wakes of outer turbines. Further, the strong wind veer associated with stable conditions results in a stretching of the wake structures, and this stretching manifests differently for inner and outer wakes. These insights can be incorporated into low-order wake models for wind farm layout optimization or for wind power forecasting.

Boelens, O. J., van der Ven, H., Oskam, B. and Hassan, A. A.

"ACCURATE AND EFFICIENT VORTEX-CAPTURING FOR ROTOR BLADE VORTEX INTERACTION; FINAL REPORT"

NLR TP-2000-051, February 2000, National Aerospace Lab., Amsterdam, The Netherlands

The objective of this paper is to present an innovative computational fluid dynamics (CFD) algorithm for the simulation of wake vortices generated by helicopter rotors. Special emphasis is placed on the CFD technology in terms of: basic requirements for these CFD algorithms, general CFD development stages, important CFD issues such as accuracy, efficiency and parallelization, and demonstration of a prototype CFD system on test cases relevant for vortex wake simulation.

Boelens, O. J., van der Ven, H., Oskam, B. and Hassan, A. A.

"BOUNDARY CONFORMING DISCONTINUOUS GALERKIN FINITE ELEMENT APPROACH FOR ROTORCRAFT SIMULATIONS"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 776-785

A numerical method has been developed for predicting the complex vortex wake for a helicopter rotor in hover and in forward flight. The method is based on the solution of the three-dimensional, compressible Euler equations expressed in an arbitrary Lagrangian Eulerian reference frame. A second-order accurate discontinuous Galerkin finite element method is used to discretize the governing equations on a hexahedral mesh. Unstructured, local mesh refinement is performed to enable prediction of the structure of the vortex wake. The capabilities of this computational fluid dynamics method are demonstrated by simulations of the flow around the Caradonna-Tung helicopter rotor in hover and simulations of the flow around the Operational Loads Survey helicopter rotor in forward flight. Accuracy of the method is assessed through comparison with wind-tunnel data, if available. Special attention is given to a rotor trimming procedure developed at the National Aerospace Laboratory/NLR and to the grid adaptation algorithm.

Boer, J. F., Hermans, C. and Pengel, K.

"EXPERIMENTAL AND THEORETICAL ASSESSMENT OF THE HELICOPTER GROUND VORTEX PHENOMENON"

NLR-TP-2002-305, June 2002, National Aerospace Laboratory, Amsterdam, The Netherlands

During recent wind tunnel tests, performed in the European 4th Framework program HELIFLOW, the position and flow characteristics of the rotorwash induced ground vortex were measured. These results were used for the verification and improvement of the NLR helicopter ground vortex calculation model, which is part of the rotorwash induced horizontal airflow calculation tool OUTWASH, currently under development for the Ministry of Defence of the Netherlands. The wind tunnel tests were performed in the Large Low-speed Facility of the German-Dutch Wind Tunnels. The use of state-of-the-art test techniques, such as Laser Light Sheet and Particle Image Velocimetry, and DLR's powered main rotor BO 105 wind tunnel model made it possible to measure the ground vortex induced velocities. The NLR ground vortex mathematical model is a tool for the prediction of the helicopter ground vortex position, shape and strength. It consists of an empirical radial wall-jet model and a set of airflow equilibrium equations. The vortex is represented by discrete filaments, while the induced velocities are calculated using Biot-Savart Law. The improved ground vortex model calculation results show a good match with the experimental ground vortex core positions and strengths data for all HELIFLOW test conditions.

Boer, J. F., Hermans, C. and Pengel, K.

"HELICOPTER GROUND VORTEX: COMPARISON OF NUMERICAL PREDICTIONS WITH WIND TUNNEL MEASUREMENTS"

NLR TP-2001-569, December 2001, National Aerospace Lab., Amsterdam, The Netherlands

In the framework of the Brite Euram project HELIFLOW, research activities were conducted aimed at knowledge acquisition in interactional aerodynamics, validation of wind tunnel test technologies and verification of related theoretical tools. This paper describes the ground vortex activities performed in Task 3 of the project, which addressed the low-speed phenomena of quartering flight. During sideward flight in ground proximity, the helicopter main rotor induced ground vortex influences the main and tail rotor inflow conditions and thus its performance. Wind tunnel tests were performed with a powered BO 105 model in the Large Low-speed Facility (LLF) of the German-Dutch Wind Tunnels (DNW). State of the art airflow test techniques were applied to measure the ground vortex flow phenomena. The in-house developed OUTWASH code was extended with several features for application within HELIFLOW. It was applied for pre-test calculations to refine the wind tunnel test matrix and to define the experimental set-up for the flow measurements by calculating the ground vortex locations. Based on the test results obtained, an OUTWASH analysis activity was performed. Specific attention was given to the numerical and experimental assessment of the ground vortex core position and velocity distribution.

Boer, M. F. and Hoffe, A. C.

"METHOD FOR REDUCING IN FLIGHT WAKE VORTICES AND AN AIRCRAFT WINGTIP ARRANGEMENT USED IN SUCH METHOD"

US Patent 8,894,018 B2, November 2014.

This invention discloses a method to break down, destabilize, or destroy an in-flight wake vortex shed from an aircraft's wing. The wingtip has a winglet mounted to an extremity of the wing, and means for actuating displacement of the winglet relative to the wing. The winglet is displaced from a stationary position, in which the in-flight wake vortex is stable, to a continuous moving condition, in which the winglet is displaced to a secondary temporary stationary position, remote from the initial stationary position, and having any angle relative to a plane extending through a vertical, longitudinal, or lateral axis of the aircraft to alter the winglet's angle of attack, and persisting in the moving condition as long as required to break down, destabilize or destroy the in-flight wake vortex. The invention includes a wingtip arrangement for use in the method and an aircraft including the wingtip arrangement.

Bofah, K. K.

"SOME REMARKS ON AIRCRAFT WAKE VORTEX ANALYSIS"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 31-46

Analysis techniques for aircraft trailing vortices are presented. Employing vortex theories by Saffman and Moore, predictive methods for vortex-induced rolling moments and coalescence time for a vortex pair are obtained. The predictions compare favorably with published data in the far field.

Bofah, K. K.

"A STUDY OF THE TRAILING VORTICES BEHIND A RING WING"

Ph.D. Thesis, 1975, California Institute of Technology, Pasadena, CA

Experiments were conducted in the Graduate Aeronautical Laboratories, California Institute of Technology Low Speed Water Channel, using laser Doppler velocimetry techniques to measure vertical and axial velocity components in the trailing vortex wake. A thin cylindrical ring wing model was tested at various axial angles of attack and free stream velocities. Velocity profiles were measured at several downstream stations from the trailing edge to 45 wing diameters downstream. The inviscid roll-up of the trailing vortex sheet shed by a ring wing was numerically examined. A line vortex representation was used to calculate the evolution of the initially cylindrical vortex sheet. The vortex sheet was found to distort in shape and then smoothly roll up into a pair of doubly connected spirals whose centers originate from approximately the center of gravity of vorticity in the upper quadrants of the ring wing's circular trailing edge. The experimental and flow visualization results are consistent with the numerical data and show that a pair of counter-rotating vortices do develop from the rolling up of the vortex sheet shed by a ring wing in an nonaxial flow. The vortices trail, downstream of the wing, with their vorticity centroids spaced by $\pi/4$ wing diameters.

Bogey, C., Bailly, C. and Juve, D.

"COMPUTATION OF FLOW NOISE USING SOURCE TERMS IN LINEARIZED EULER'S EQUATIONS"

AIAA Journal, Vol. 40, No. 2, February 2002, pp. 235-243

An acoustic analogy using linearized Eulers equations (LEE) forced with aerodynamic source terms is investigated to compute the acoustic far field. This hybrid method is applied to three model problems simulated by solving Navier-Stokes equations. In this way, its validity is estimated by comparing the predicted acoustic field with the reference solution given directly by the Navier-Stokes equations. The noise radiated by two corotating vortices is studied: first, in a medium at rest and, second, in a mean sheared flow with no convection velocity. Then the sound field generated by vortex pairings in a subsonic mixing layer is investigated. In this case, a simplified formulation of LEE is proposed to prevent the exponential growth of instability waves. The acoustic fields obtained by solving LEE are in good agreement with the reference solution. This study shows that the source terms introduced into the LEE are appropriate for free sheared flows and that acoustic-mean flow interactions are properly taken into account in the wave operator.

Bogue, R. K. and Jentink, H. W.

"OPTICAL AIR FLOW MEASUREMENTS IN FLIGHT"

RTO AGARDograph 160, Vol. 20, December 2003

The goal of this AGARDograph is to provide an introductory practical overview of in-flight optical flow measurement techniques. This document is written to aid an instrumentation engineer or research scientist in making non-intrusive flow measurements on an aircraft. It is hoped that this document will be particularly useful for the technologist with a limited background in optical theory and limited experience in applying optical technology. The experience of the authors and numerous other contributors has been infused here to provide guidance in avoiding expensive non-productive diversions that can occur when applying optical technology for the first time in the flight environment. This AGARDograph provides basic knowledge and techniques necessary for assessing the applicability of optical measurements and addressing effective optical measurement techniques in flight. Key aspects of optical measurements are discussed and the tradeoffs are identified, as they are currently understood. Basic components of optical measurement systems are discussed and key requirements are identified. Specific systems designed for a variety of applications are discussed to provide insight for the reader.

Boguslawski, A., Tyliczszak, A. and Drobniak, S.

"LES PREDICTIONS OF ROUND ISOTHERMAL AND HEATED JETS"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

The main aim of the work presented was to perform the LES calculations of the isothermal and heated air jet to study the mechanism of the jet instability and the influence of some governing parameters like density ratio of the jet to ambient fluid, shear layer thickness and turbulence level at the nozzle outlet. The LES results were verified with experimental data. The experimental set-up was

designed in such a way that the shear layer at the nozzle outlet was laminar to not disturb formation of the coherent vortices resulting from the jet instability and to generate conditions for absolute instability in the case of hot jet. Very low turbulence level at the nozzle exit was obtained by application of cubic equation nozzle with very high contraction ratio and careful design of the settling chamber. Within the experiment the shear layer thickness at the nozzle exit was controlled by using the extension tubes variable lengths attached to the main nozzle. The LES calculations were aimed mainly at the prediction of the absolutely unstable mode of hot jet hence the effort was concentrated on the case of relatively thick shear layer. The LES calculations were performed with the use of in-house LES code SAILOR - Spectral And compact Differences High Order Code for Low Mach Number LES). The code uses the Fourier spectral approximation in the lateral directions and compact differences in the longitudinal one. To study variable density flow for low Mach number an extension of Navier-Stokes and energy equations was applied. For integration of the system of equation with respect to time low-storage three stage Runge-Kutta method was used and within each time step the projection method was applied for pressure.

Bohbot, J., Grondin, G., Corjon, A. and Darracq, D.

"A PARALLEL MULTIGRID CONSERVATIVE PATCHED/SLIDING MESH ALGORITHM FOR TURBULENT FLOW COMPUTATION OF 3D COMPLEX AIRCRAFT CONFIGURATIONS"

AIAA Paper No. 2001-1006, Reno, NV, January 2001

Body fitted structured grid generation is a crucial step in the computation of flow around complex aircraft configurations. The structured body fitted mesh inevitably leads to dense meshes even in zones where gradients are expected to be low. The challenge is to develop an efficient way to simplify the grid generation for complex configurations in transonic flow without wasting points. In this paper, a 3D patched/sliding mesh algorithm is described. The patched grid algorithm is associated with the LU-SGS scheme for implicit time integration and a multigrid technique. The turbulence terms are approximated by the Baldwin-Lomax algebraic model or by the one equation Spalart-Allmaras model. The efficiency of the patched grid algorithm is demonstrated with several referenced test cases. Finally, computations over the AS28G aircraft (fuselage, wing, pylon, nacelle) using the patched grid algorithm are presented. An unsteady calculation of pitching NACA0012 airfoil is analyzed to assess the performance of moving grid using the sliding mesh algorithm.

Bohl, D. and Koochesfahani, M. M.

"MOLECULAR TAGGING VELOCIMETRY MEASUREMENTS OF AXIAL FLOW IN A CONCENTRATED VORTEX CORE"

Physics of Fluids, Vol. 16, No. 11, November 2004, pp. 4185-4191

The characteristics of the axial flow within the core of a concentrated line vortex are investigated using molecular tagging velocimetry (MTV). A well-defined array of isolated vortices of alternating sign is generated in the wake of a NACA-0012 airfoil pitching sinusoidally at small amplitude and high

reduced frequencies. The circulation and peak vorticity of the vortices are varied by the choice of oscillation frequency. Interaction of these two-dimensional vortices with the walls of the test section generates an axial flow within the vortex cores. The magnitude of the axial flow and its spatial/temporal characteristics are quantified using the MTV technique. Results show that the peak axial flow speeds can be very high, of the order maximum swirl speed of the vortices. The maximum axial speed ratio (maximum axial speed normalized by maximum swirl speed) is found to vary in the range 0.6-1.0 for the parameters investigated here. Initially, the axial flow is spatially confined in isolated structures corresponding to the core of vortices. As the vortex convects downstream, however, the spatial structure of axial flow changes from isolated regions to a continuous region for the highest reduced frequency investigated here. This change in structure is correlated with a significant decrease in the peak axial flow speed.

Bohl, D. G. and Koochesfahani, M. M.

"MTV MEASUREMENTS OF AXIAL FLOW IN CONCENTRATED VORTEX CORES"

Physics of Fluids, Vol. 16, No. 11, Nov. 2004, pp. 4185-4191

The characteristics of the axial flow within a concentrated vortex core are investigated using Molecular Tagging Velocimetry (MTV). A well-defined array of isolated vortices of alternating sign is generated in the wake of a NACA-0012 airfoil pitching sinusoidally at small amplitude and high reduced frequencies. The circulation and peak vorticity of the vortices are varied by the choice of oscillation frequency. Interaction of these 2-D vortices with the walls of the test section generates an axial flow within the vortex cores. The magnitude of the axial flow and its spatial/temporal characteristics are quantified using the MTV technique. Results show that the peak axial flow speeds can be very high, of order maximum swirl speed of the vortices. It is found that maximum swirl ratio (axial speed normalized by swirl speed) was between 0.6 and 1.0 of the swirl velocity for the range of parameters investigated. The axial flow is initially confined in isolated structures corresponding to the vortices created by the airfoil oscillation. If the reduced frequency is high enough, the structure of the axial flow changes from isolated structures to a continuous region of axial flow. The change in structure is correlated with a decrease in the peak axial flow speed.

Bohne, A. R.

"COMPARISON OF IN-SITU AIRCRAFT AND GROUND-BASED DOPPLER RADAR TURBULENCE MEASUREMENTS"

AIAA Paper 1989-0790, January 2019, January 1989, Reno, NV.

Spatially and temporally collocated Doppler radar and instrumented aircraft data acquired during the Joint Agency Turbulence Experiment are analyzed. The radar Doppler spectrum velocity and variance are utilized in structure function and variance-based methods to develop a methodology for remotely detecting hazardous turbulence. Aircraft gust data from 34 thunderstorm penetrations serve as 'ground truth'. The analyses show that the large-scale quasi-stationary storm winds can significantly influence

the measurements and much care must be utilized to separate their effects from the smaller-scale turbulence field. Use of radar Doppler velocity in structure function analysis usually results in severe underestimation of the turbulence intensity. Use of a Doppler spectrum variance-based methods employing a modeled turbulence field with a maximum effective outer scale of .5-2 km is found quite effective in delineating weak to severe turbulence regimes.

Bohne, A. R.

"COMPARISON OF IN-SITU AIRCRAFT AND GROUND-BASED DOPPLER RADAR TURBULENCE MEASUREMENTS"

AIAA Paper 1989-0790, January 2019, January 1989, Reno, NV.

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Bohning, P.

"AKUSTISCHE LOKALISIERUNG VON WIRBELSCHLEPPEN"

Ph.D. Thesis, April 2006, Technical University of Berlin, Berlin, Germany

Wake vortices are generated behind aircraft because of the lift and a finite aircraft wing span. They consist of two strong counter-rotating vortices which pose potential hazards on following aircraft. The aircraft separation rules introduced to ensure safety during landing and take-off is one of the most important constraints limiting the capacity of highly frequented airports. To cope with the expected increase in air-traffic and aircraft size, current research activities concentrate on aircraft design modifications and the development of wake vortex detection systems. Experience shows that wake vortices of landing aircraft are audible. In the framework of this thesis the sound emission of wake vortices and their detection and characterization by means of microphone arrays were studied. A potential sound generating mechanism, the interaction of primary and secondary vortex structures, and the resulting spectral properties were investigated in a numerical study using LES and Acoustic Analogy methods. It was demonstrated that the secondary structures are accelerated as they move closer to the vortex cores of the primary structures. Since accelerated vorticity is a known source of sound, strongest sources are expected in the vicinity of the cores of the primary vortex structures. A correlation of the spectral properties of the sound emission and the vortex characteristics revealed a

relation between the rotation frequency f_r of the primary vortex cores and the frequency f_a of maximal sound pressure level, $f_a \sim 0.8 f_r$. To experimentally validate the results of the numerical study, the sound of wake vortices of landing aircraft was measured in three fly-over tests applying microphone arrays. The expectation that the dominant sound sources are in the vicinity of the vortex cores was proven by the experimental results. A comparison of the sound pressure spectra revealed the existence of two classes of spectra. The aircraft types of Airbus and Boeing belong to different classes. Two maxima were found in the vortex noise spectra, at $f_1 \sim 12\text{Hz}$ and $f_2 \sim 100\text{Hz}$. The origin of the first maxima was not identified since the microphone array was too small to resolve the sound sources at frequencies below 40Hz . The second maxima could be clearly related to the vortex cores. The results demonstrated that wake vortices can be detected and characterized by its generated and radiated sound. [In German.]

Bohning, P. and Michel, U.

"ACOUSTIC PROPERTIES OF AIRCRAFT WAKE VORTICES"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-001, September 2007, pp. 1039-1048

The noise generation by aircraft wake vortices has been studied numerically and experimentally. The numerical study revealed a relation between the circulation, the vortex core size, and the frequency of the peak level in the vortex noise spectra. The experimental data were obtained in measurements at airports by applying phased microphone arrays. It has been found that sound sources are closely located to the vortex cores. The focused noise spectra of the wake vortices of all measured aircraft types are dominated by two maxima. The second maximum at $f = 100\text{ Hz}$ is clearly caused by wake vortices. The origin of the first at f of about 10 Hz has not been identified. Wake vortices were acoustically detected in 80 percent of the flyovers. Lowest detection rates were observed for the newer aircraft types Airbus A319, A320 and Boeing 737-800. A comparison of the wake trajectories measured by phased microphone arrays and LIDAR revealed that the detection capability of the latter is superior.

Bohning, P., Baumann, R., Michel, U and Gerz, T.

"NUMERICAL STUDY OF WAKE VORTEX NOISE USING LES AND AN ACOUSTIC ANALOGY METHOD"

EUROMECH Colloquium No. 467, Turbulent Flow and Noise Generation, Marseille, France, July 2005

Wake vortices of landing aircraft emit a faint noise that is audible when the wind speed is low. The noise is most likely related to aerodynamic parameters of the vortices. In recent years, it has been demonstrated that wake vortices can be localized and their noise spectra can be determined by means of microphone arrays. Noise sources are found to be located close to the vortex cores. To improve the understanding of the sound generating mechanism and the relation between aerodynamic wake parameters and noise emission, wake vortex noise was studied numerically. In the present work, the flow field of a system of four vortex filaments was calculated by 3D LES. Its noise emission was

calculated by making use of an acoustic analogy method. The results show that the peak frequency in a wake noise spectrum is likely related to the core size of the wake vortices.

Boldes, U., Delnero, J. S., Colman, J., Martinez, M. A. and Maranon-DiLeo, J.

"LIFT AND DRAG BEHAVIOR OF A LOW REYNOLDS WING SECTION SUBMITTED TO A NEARBY STREAM WISE VORTEX"

AIAA Paper No. 2008-340, Reno, NV, January 2008

The purpose of this work is to determine the influence of spiral vortical structures upon low Reynolds number airfoils. Our main goal is to find out how such vortical structures, generated by a delta wing, modify the aerodynamic coefficients and the overall behavior of those airfoils. The tip vortex wake produced by one aircraft could affect other aircrafts in different ways over other airplanes depending on whether it flows under, over or across its wing. In all cases the fluid pattern will influence the local circulation affecting the overall lift. The purpose of this work is to study this influence. The instantaneous flow velocities inside and outside the vortices will be measured by means of a hot wire anemometry (HWA). The tested airfoil is a modified Eppler 387. The experiments were carried out in a low turbulence flow (1.8%) at a Reynolds number of 350.000 (based on the airfoil chord and on the free stream velocity).

Bollman, J. R.

"WAKE VORTEX ADVISORY SYSTEM OPERATIONAL TEST AND EVALUATION"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 335-341

The objectives of the operational test and evaluation of the Vortex Advisory System (VAS) are described. The critical issues on the operational test and evaluation of VAS may be simplified as: what are the procedural implications of the system and how will operating efficiency of the airport facilities be affected?

Boluriaan, S. and Morris, P. J.

"TWO-DIMENSIONAL SIMULATIONS OF WAKE VORTEX DETECTION USING RASS"

AIAA Paper 2001-0984, January 2001, Reno, NV.

A parallel code is developed to numerically simulate wake vortex detection using a Radio Acoustic Sounding System (RASS). The code is written in Fortran 90 with the Message Passing Interface (MPI) for parallel implementation. The numerical simulation solves simultaneously the linearized Euler equations for a non-uniform mean flow and the Maxwell equations for a non-homogeneous medium. The radar transmitter and receiver antennas are modeled using an array of point sources and a beamforming technique, respectively. Many features of the RASS are explored using the numerical simulation. First, a

uniform mean flow is considered and the RASS simulation is performed for two different types of incident acoustic field: a short single frequency acoustic pulse and a continuous broadband acoustic source. Both monostatic and bistatic configurations are examined and their results are compared. Taylor and Oseen vortex velocity profiles are used as a vortex model, and the mean flow fields are reconstructed from the backscattered electromagnetic signal using the Abel transform. The effect of radar beam width is also shown.

Boluriaan, S. and Morris, P. J.

"TWO-DIMENSIONAL SIMULATIONS OF WAKE VORTEX DETECTION USING RADIO ACOUSTIC SOUNDING SYSTEMS"

AIAA Journal, Vol. 40, No. 11, November 2002, pp. 2247-2256

A parallel code is developed to simulate numerically wake vortex detection using a radio acoustic sounding system (RASS). The code is written in FORTRAN 90 with the message passing interface for parallel implementation. The numerical simulation solves simultaneously the linearized Euler equations for a nonuniform mean flow and the Maxwell equations for a nonhomogeneous medium. The radar transmitter and receiver antennas are modeled using an array of point sources and a beam-forming technique, respectively. Many features of the RASS are explored using the numerical simulation. First, a uniform mean flow is considered, and the RASS simulation is performed for two different types of incident acoustic field: a short single-frequency acoustic pulse and a continuous broadband acoustic source. Both monostatic and bistatic configurations are examined, and their results are compared. Taylor and Oseen vortex velocity profiles are used as sample models, and their mean flowfields are reconstructed from the backscattered electromagnetic signal using the Abel transform. The effect of radar beam width is also considered, as are the issues of non-axisymmetric and interacting vortices.

Boluriaan, S. and Morris, P. J.

"NUMERICAL SIMULATION OF WAKE VORTEX DETECTION USING A RADIO ACOUSTIC SOUNDING SYSTEM"

AIAA Journal, Vol. 39, No. 6, June 2001, pp. 1097-1105

A parallel, two-dimensional Euler, one-dimensional, Maxwell code is developed to numerically simulate wake vortex detection using a radio acoustic sounding system. The code is written in Fortran 90 with the message passing interface for parallel implementation. The main difficulty with a time-accurate simulation is the number of samples required to resolve the Doppler shift in the scattered electromagnetic signal. Even for a one-dimensional simulation with typical scatterer size, the CPU time required to run the code is far beyond currently available computer resources. Two alternatives that overcome this problem are described. In the first, the code is run for a fictitious speed of light. Second, the governing differential equations are recast to remove the carrier frequency and solve only for the frequency shift using an implicit scheme with large time steps. The numerical stability characteristics of

the resulting discretized equation with complex coefficients are shown. The code is run for both the approaches with Taylor and Oseen vortex velocity profiles. Finally, the Abel transform is applied to the outputs of both explicit and implicit schemes, and the wake vortex velocity field is retrieved with very good accuracy.

Boluriaan, S. and Morris, P. J.

"PARALLEL NUMERICAL SIMULATION OF WAKE VORTEX DETECTION USING RASS"

AIAA Paper No. 2000-2073, Lahaina, HI, June 2000.

A parallel, two-dimensional Euler, one-dimensional Maxwell code is developed to numerically simulate wake vortex detection using a Radio Acoustic Sounding System. The code is written in Fortran 90 with the Message Passing Interface for parallel implementation. The main difficulty with a time accurate simulation is the number of samples required to resolve the Doppler shift in the scattered electromagnetic signal. Even for a 1D simulation with typical scatterer size, the CPU time required to run the code is far beyond currently available computer resources. Two alternatives that overcome this problem are described. In the first the code is run for a fictitious speed of light. Second, the governing differential equations are recast to remove the carrier frequency and solve only for the frequency shift using an implicit scheme with large time steps. The numerical stability characteristics of the resulting discretized equation with complex coefficients are shown. The code is run for both the approaches with Taylor and Oseen vortex velocity profiles. Finally, the Abel transform is applied to the outputs of both explicit and implicit schemes, and the wake vortex velocity field is retrieved with very good accuracy.

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"TWO-DIMENSIONAL SIMULATIONS OF WAKE VORTEX DETECTION USING RASS"

AIAA Journal, Vol. 39, No. 6, 2001, pp. 1097-1105

A parallel code is developed to numerically simulate wake vortex detection using a Radio Acoustic Sounding System (RASS). The code is written in Fortran 90 with the Message Passing Interface (MPI) for parallel implementation. The numerical simulation solves simultaneously the linearized Euler equations for a non-uniform mean flow and the Maxwell equations for a non-homogeneous medium. The radar transmitter and receiver antennas are modeled using an array of point sources and a beamforming technique, respectively. Many features of the RASS are explored using the numerical simulation. First, a uniform mean flow is considered and the RASS simulation is performed for two different types of incident acoustic field: a short single frequency acoustic pulse and a continuous broadband acoustic source. Both monostatic and bistatic configurations are examined and their results are compared. Taylor and Oseen vortex velocity profiles are used as a vortex model, and the mean flow fields are reconstructed from the backscattered electromagnetic signal using the Abel transform. The effect of radar beam width is also shown.

Bond, D. and Johari, H.

"IMPACT OF BUOYANCY ON VORTEX RING DEVELOPMENT IN THE NEAR FIELD"

Exp. Fluids, Vol. 48, 2010, pp. 737-745.

The development of a buoyant vortex ring in the near field was examined experimentally, and the findings were compared with those of a non-buoyant ring with a similar Reynolds number. The experiments were performed in a water tank, and the vortices were produced by a cylindrical tube of aspect ratio 2. Laser sheet flow visualization and PIV measurements were carried out. In the near field, the initial column of the buoyant fluid breaks down due to the presence of Rayleigh-Taylor instability at the buoyant fluid interface. Subsequently, a large diameter vortex ring with a large spreading rate, compared with the non-buoyant ring, emerges. The celerity of buoyant vortex continued to decrease throughout the range examined, in contrast to the constant celerity of the non-buoyant ring. The vorticity in the core of buoyant and non-buoyant vortex rings is symmetric and has a Gaussian distribution. However, the buoyant vortex ring evolves into a thin core ring, whereas the non-buoyant ring becomes a thick core ring shortly after the ring formation. This difference is brought on by the rapid entrainment and the significant growth of the buoyant ring following the breakup of the initial formation.

Bone, R., Mundra, A. and Olmos, B. O.

"PAIRED APPROACH OPERATIONAL CONCEPT"

IEEE Digital Avionics Systems Conference, Vol. 1, October 2001, pp. 5B3-1-5B3-14

The paired approach procedure is intended to facilitate IFR approaches to closely spaced parallel runways i.e., runways separated by less than 2500 feet. Parallel ILS approaches cannot currently be conducted under instrument meteorological conditions to such runways. The paired approach procedure requires aircraft to maintain longitudinal separations within a specific band on approach to the runways such that protection is provided against collision as well as wake vortex hazards. The procedure requires air traffic control to pair eligible aircraft and deliver them to the final approach courses within certain longitudinal tolerances. The flight crew of the trailing aircraft then conducts the paired approach procedure with a set of cockpit-based spacing tools. These spacing tools help the flight crew to achieve and maintain a defined longitudinal spacing prior to the final approach fix. Real time simulations were conducted with line pilots and full performance level controllers in a medium fidelity simulation. The simulation capability included a commercial twin jet flight deck and an ATC platform, which in turn, were used to define flight deck tasks, develop cockpit display and spacing tool requirements, and define ATC procedures and controller tasks. This paper describes these ATC procedures, pilot and controller tasks and cockpit display requirements. It also discusses ways in which the spacing concept and tools so developed are being applied and developed further for other approach spacing applications.

Booth, Jr., E. R. and Humphreys, Jr., W. M.

"TRACKING AND CHARACTERIZATION OF AIRCRAFT WAKES USING ACOUSTIC AND LIDAR MEASUREMENTS"

AIAA-2005-2964, Monterey, CA, May 2005

Data from the 2003 Denver International Airport Wake Acoustics Test are further examined to discern spectral content of aircraft wake signatures, and to compare three-dimensional wake tracking from acoustic data to wake tracking data obtained through use of continuous wave and pulsed lidar. Wake tracking data derived from acoustic array data agree well with both continuous wave and pulsed lidar in the horizontal plane, but less well with pulsed lidar in the vertical direction. Results from this study show that the spectral distribution of acoustic energy in a wake signature varies greatly with aircraft type.

Boquet, M., Ribstein, B., Parmentier, R., Sauvage, L. and Cariou, J.-P.

"ANALYSIS AND OPTIMISATION OF PULSED DOPPLER LIDAR WIND PROFILE MEASUREMENT PROCESS IN COMPLEX TERRAIN"

Proceedings 15th Coherent Laser Radar Conference, June 2009, Toulouse, France, pp. 117-120.

Accuracy of Lidar remote sensors for wind energy has been previously reported. Coherent Doppler lidars have shown very high correlation with calibrated cup anemometers in flat terrain, both onshore and offshore. However, in more complex terrain, not only more turbulent air flow but also loss of flow homogeneity happens, and remote sensors measurement process need to be closely examined. We compare and simulate cup's point and lidar's volume measurements to understand and explain for the two sensor's response. We put in evidence the main error term in the horizontal and vertical wind speed retrieval. Geometrical optimizations of the WINDCUBE (TM) measurement process are also investigated to get more reliable wind speed estimate. We show our conclusions and the results of the CFD simulation performed on a Spanish complex terrain case.

Borener, S. S., Guzhva, V. S., Crook, I. and Fraga, R.

"SAFETY ASSESSMENT OF IMPLEMENTED NEXTGEN OPERATIONAL IMPROVEMENTS"

Transportation Research Procedia, Vol. 14, 2016, pp. 3731-3740.

Since most NextGen Operational Improvements (OIs) have been implemented recently, there is no traditional safety statistics, such as the number of accidents and/or incidents available to perform their formal safety evaluations. In this paper we present a process of safety assessment using precursors that may lead to unsafe outcomes. We use the radar track data to estimate traffic separations before and after NextGen OI implementation at Memphis International Airport (MEM). The FAA implemented Phase I of wake re-categorization (RECAT) separation standards at MEM in November 2012. We examine the counts of wake, proximity, and anomalous events for two 30-day samples of pre- and post-RECAT periods. While the paper focuses on the methodology and is not intended to provide a detailed

safety evaluation of RECAT, the findings suggest that RECAT implementation did not adversely affect the air traffic safety.

Borer, N. K., Barrows, T. M., Levine, D. M., Page, L. A. and Benney, R. J.

"FORMATION AIRDROP SCALING EFFECTS ON AIRCRAFT WAKE VORTEX FORMATION AND INTERACTION"

AIAA Paper 2013-0361, January 2013, Grapevine, TX.

A parametric model for location and strength of aircraft wake vortices is used to determine the potential for hazardous wake vortex/personnel interaction for different operational, environmental, and formation geometry parameters across two scaling studies. In the first study, 729 variations of a four-aircraft formation resulted in 39 geometries with potential for adverse jumper-wake vortex interactions. A second six-aircraft study, with finer variations in element-to-element spacing, indicated adverse interactions in 575 of the 1,224 variations considered. In both experiments, the formations with adverse interactions included nontrivial yet predictable combinations of lateral and longitudinal spacing, airspeed, and crosswind, with a noticeable lack of sensitivity to aircraft weight. These results can lead to more flexible formation airdrop planning guidelines by identifying the combinations of conditions that lead to adverse wake vortex encounters.

Borough, C. K.

"ELECTRO-OPTICAL VORTEX STUDIES FOR LARGE AIRCRAFT"

TR 1976, January 1976, Naval Electronics Lab. Center, San Diego, CA

Several promising approaches to the wake vortex problem have been recommended by electro-optical industries. Most of them recommend taking advantage of the concentration of CO₂ in the 14-to-16-micron region.

Borovoy, V. Y.

"FLOW PATTERNS AND HEAT EXCHANGE IN SUPERSONIC VORTEX"

SPC-93-4045, 1994, Central Aerohydrodynamics Institute, Moscow, Russia.

In many cases vortices are being generated on the aircraft surface: on the upper wing and body surfaces, in the vicinity of the deflected fins. They can essentially influence pressure distribution and heat transfer. The vortex generated on the upper surface of a body or a wing can encounter the shock wave in front of the fin, located downstream. Another example is: interaction of the vortex, generated by a canard, a strake or a nose flap intended for aircraft trimming with the wing or fin shock wave. A case important for practical purposes is described in: interaction between the vortex and inlet shock waves qualitatively changes the inlet entry flow pattern. A similar phenomenon can be observed in the case of interaction of the vortex generated in the inlet with the pylon of the air-breathing jet

combustion chamber. In this context, it is worthwhile to investigate the vortex structure and its interaction with the streamlined body.

Borovoy, V. Y., Kubyshina, T. V. Skuratov, A. S. and Yakovleva, L. V.

"VORTEX IN A SUPERSONIC FLOW AND ITS INFLUENCE ON BLUNT BODY FLOW AND HEAT TRANSFER"

Fluid Dynamics, Vol. 35, No. 5, 2000, pp. 682-690

The dissipation of a tip vortex generated by a rectangular wing and the stagnation pressure and temperature distributions within the vortex are experimentally investigated. The interaction of the vortex with the bow shock ahead of a sphere and the heat flux distribution over the spherical surface are studied. The experiments were carried out at the Mach number $M = 3$ and the unit Reynolds numbers $Re = 11,000,000$ and $37,000,000$.

Boschetti, P. J. and Cardenas, E. M.

"NONLINEAR MODELS FOR REPRESENTING AERODYNAMIC COEFFICIENTS OF A WING IN GROUND EFFECT"

AIAA Paper 2018-1759, January 2018, Kissimmee, FL.

The aim of the present work is to develop a model for representing lift, drag, and pitching moment coefficients of a wing and/or flight vehicle in ground effect when the height is a function of time. By assuming that the airplane is a rigid-body, the altitude variations are sufficiently small that the flow density, the kinematic viscosity, and the dynamic pressure remain constant, and by including the non-dimensional height into the aircraft states, it was possible to obtain a general longitudinal aerodynamic model of an airplane in ground effect. In this model, the non-dimensional stability derivatives are functions of the non-dimensional height, and the nonlinear effects in ground effect are represented by a group of terms, which are equal to zero in steady flight close to ground. Three cases are considered to represent the nonlinear effects that occur in a dynamic ground effect phenomenon: 1) They can be represented by the h derivative, 2) the h derivatives are also functions of the angle of attack, and 3) there is an additional term to represent the unsteady flow effects. It is concluded that the non-dimensional h derivatives are linked to a specific history of the flight path or trajectory due to the flow downstream.

Boschetti, P. J., Quijada, G. M. and Cardenas, E. M.

"DYNAMIC GROUND EFFECT ON THE AERODYNAMIC COEFFICIENTS USING A PANEL METHOD"

Journal of Aircraft, Vol. 54, No. 2, March-April 2017, pp. 835-841.

The ground proximity of a wing in flight produces changes in its aerodynamics characteristics; the induced drag is reduced and the lift is increased. The most significant findings of this study can be summarized as follows: (1) The sink rate produces significant variations in lift, induced drag, and

pitching moment coefficients of a wing and this must be considered in flight simulation and flight control system design in ground effect. (2) Nonlinear models of a wing in dynamic ground effect were developed to model flare and descent at constant sink rate, meaning that each maneuver needs a specific model.

Bosnyakov, I. S. and Sudakov, G. G.

"FEATURES OF AIRPLANE VORTEX WAKE DECAY IN CRUISE FLIGHT AND IN LAND PROXIMITY"

International Conference on the Methods of Aerophysical Research (ICMAR 2016), AIP Conference Proceedings, Vol. 1770, 2016, pp. 030122-1 to 030122-9.

The cases of the vortex wake decay after the large aircraft are considered for the case of cruise flight and near the ground. It is shown that the scenarios of destruction process are principally different from each other. The physical features of the phenomenon are described and the two models for description of such phenomenon are compared.

Bossel, H. H.

"VORTEX EQUATIONS: SINGULARITIES, NUMERICAL SOLUTION, AND AXISYMMETRIC VORTEX BREAKDOWN"

NASA CR-2090, July 1972, University of California, Santa Barbara.

A method of weighted residuals for the computation of rotationally symmetric quasi-cylindrical viscous incompressible vortex flow is presented and used to compute a wide variety of vortex flows. The method approximates the axial velocity and circulation profiles by series of exponentials having $(N + 1)$ and N free parameters, respectively. Formal integration results in a set of $(2N + 1)$ ordinary differential equations for the free parameters. The governing equations are shown to have an infinite number of discrete singularities corresponding to critical values of the swirl parameter. The computations point to the controlling influence of the inner core flow on vortex behavior. They also confirm the existence of two critical swirl parameter values: one separates vortex flow which decays smoothly from vortex flow which eventually breaks down, and the second is the first singularity of the quasi-cylindrical system, at which point physical vortex breakdown is thought to occur.

Bossel, H. H.

"INVISCID AND VISCOUS MODELS OF THE VORTEX BREAKDOWN PHENOMENON"

Ph.D. Thesis, Report No. A.S. 67-14, August 1967, University of California, Berkeley, CA

In the case of high swirl and large Reynolds number, the Navier-Stokes equations for rotationally symmetric incompressible flow are shown to reduce to (1) a viscous parabolic system for slender (quasi-cylindrical) flows and (2) an inviscid elliptic system for expanding (or contracting) flows. The inviscid system is solved for the case of flow with initial rigid rotation in a cylindrical stream surface.

Assuming different downstream boundary conditions, Fourier-Bessel series solutions are computed for the supercritical (non-oscillatory) case and plotted. For very high swirl values, closed and open bubbles of recirculating fluid are obtained for certain cases, where the closed bubbles resemble those observed in vortex tube experiments. The viscous slender problem is formulated in an integral method using approximating functions for axial velocity and circulation which satisfy boundary and asymptotic requirements. Weighting functions are used to generate a linearly independent set of equations of sufficient number to determine the coefficients in the velocity and circulation approximations as functions of one (the axial) coordinate. The formulation is for any order of approximation. Computational difficulties appear near the suspected breakdown point. Flows resembling breaking flows are obtained.

Bossel, H. H.

"VORTEX BREAKDOWN FLOWFIELD"

Phys. Fluids, Vol. 12, No. 3, March 1969, pp. 498-507

The Navier-Stokes equations for incompressible rotationally symmetric vortex flow at high swirl and large core Reynolds number are shown to approximate to the equation of inviscid rotating flow in regions where rigid rotation results from viscous action. Series solutions at high supercritical swirl values near the critical one under the condition of flow retardation near the axis are found to exhibit the experimentally observed features of vortex breakdown flows: bulges of decelerated flow, or bubbles of recirculating fluid, with reversed axial and swirl velocities near the axis. It is concluded that the vortex breakdown in vortex tubes and on delta wings is neither due to hydrodynamic instability, nor is it a phenomenon akin to the hydraulic jump. Rather it is a regular feature of the solution of the equations of motion under the given conditions.

Boswinkle, Jr., R. W.

"AIRCRAFT VORTEX WAKES"

Proceedings of Annual Corporate Aircraft Safety Seminar, Flight Safety Foundation, May 1970

An aircraft which is producing lift leaves a rotating flow field behind each wing as it flies forward. There is usually one pair of oppositely rotating flow fields, or vortices, extending downstream from each wing tip and moving downward. Each vortex has a core region in which the rotational velocities build up from zero in the center to some maximum velocity at the edge of the core. If another aircraft crosses laterally through the core of each vortex, it will be subjected to an up-flow, a down-flow, and then another up-flow. Hazards connected with these air motions for a light aircraft are discussed.

Boswinkle, Jr., R. W.

"VORTEX WAKE TURBULENCE"

Flight Safety Foundation 23rd International Air Safety Seminar, Washington, DC, 1970

The talk highlighted the status of the vortex wake problem from the aircraft operator's standpoint. The vortex wake is described, accident statistics discussed, status of knowledge of vortex wake turbulence indicated, and example results of some measurements presented.

Bottausci, F. and Petitjeans, P.

"VISUALIZATIONS OF STRETCHED VORTICES"

Lecture Notes in Physics, Vol. 555, 2000, pp. 124-134

We study the structure, dynamics, and the instabilities of a stretched vortex in two different experiments: The first experiment generates a vortex by stretching the vorticity of a laminar boundary layer on a plane wall in a water channel. The second experiment generates a vortex between two co-rotating discs with a suction through a hole in the center of each disc. These vortices model the filaments of vorticity of turbulent flow. Visualizations are presented which show the structure and the instabilities of these stretched vortices.

Boudaoud, W., Yahiaoui, T., Imine, B. and Imine, O.

"EFFECT OF AN EXTERNAL VORTEX ON THE UAV AERODYNAMIC PERFORMANCES"

EPJ Web of Conferences, Vol. 25, 2012, pp. 01104-1 to 01104-6.

In this present work, the CFD and wind tunnel are used to investigate the effect of an external vortex around an UAV to obtain initial estimates of lift and drag coefficients with flow velocity of 30 meters per second for various angles of attack. The model of Spalart-Allmaras turbulence is used for the investigation of the complex flow around the UAV. The wind tunnel and CFD results are compared and appropriate error bands placed on the data.

Boulanger, N., Meunier, P. and Le Dizes, S.

"TILT-INDUCED INSTABILITY OF A STRATIFIED VORTEX"

J. Fluid Mech., Vol. 596, 2008, pp. 1-20

This experimental and theoretical study considers the dynamics and the instability of a Lamb-Oseen vortex in a stably stratified fluid. In a companion paper, it was shown that tilting the vortex axis with respect to the direction of stratification induces the formation of a rim of strong axial flow near a critical radius when the Froude number of the vortex is larger than one. Here, we demonstrate that this tilt-induced flow is responsible for a three-dimensional instability. We show that the instability results from a shear instability of the basic axial flow in the critical-layer region. The theoretical predictions for the wavelength and the growth rate obtained by a local stability analysis of the theoretical critical-layer profile are compared to experimental measurements and a good agreement is

observed. The late stages of the instability are also analyzed experimentally. In particular, we show that the tilt-induced instability does not lead to the destruction of the vortex, but to a sudden decrease of its Froude number, through the turbulent diffusion of its core size, when the initial Froude number is close to 1. A movie is available with the online version of the paper.

Boulanger, N., Meunier, P. and Le Dizes, S.

"STRUCTURE OF A STRATIFIED TILTED VORTEX"

J. Fluid Mech., Vol. 583, 2007, pp. 443-458

The structure of a columnar vortex in a stably stratified fluid is studied experimentally and theoretically when the vortex axis is slightly tilted with respect to the direction of stratification. When the Froude number of the vortex is larger than 1, we show that tilting induces strong density variations and an intense axial flow in a rim around the vortex. We demonstrate that these characteristics can be associated with a critical-point singularity of the correction of azimuthal wavenumber $m=1$ generated by tilting where the angular velocity of the vortex equals the Brunt-Vaisala frequency of the stratified fluid. The theoretical structure obtained by smoothing this singularity using viscous effects (in a viscous critical-layer analysis) is compared to particle image velocimetry measurements of the axial velocity field and visualizations of the density field and a good agreement is demonstrated.

Bourdin, P., Gatto, A. and Friswell, M. I.

"AIRCRAFT CONTROL VIA VARIABLE CANT-ANGLE WINGLETS"

J. Aircraft, Vol. 45, No. 2, March-April 2008, pp. 414-423

This paper investigates a novel method for the control of 'morphing' aircraft. The concept consists of a pair of winglets with adjustable cant angle, independently actuated and mounted at the tips of a baseline flying wing. The general philosophy behind the concept was that for specific flight conditions such as a coordinated turn, the use of two control devices would be sufficient for adequate control. Computations with a vortex lattice model and subsequent wind-tunnel tests demonstrate the viability of the concept, with individual and/or dual winglet deflection producing multi-axis coupled control moments. Comparisons between the experimental and computational results showed reasonable to good agreement, with the major discrepancies thought to be due to wind-tunnel model aeroelastic effects.

Bouremel, Y., Yianneskis, M. and Ducci, A.

"VORTICITY AND STRAIN DYNAMICS FOR VORTEX RING MIXING PROCESS"

14th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 2008

Mixing is of paramount importance in the chemical, petrochemical, and pharmaceutical industries, as almost half of their production lines involve mixing in stirred vessels, but further optimization of related processes is hampered by incomplete understanding of the fluid mechanics of mixing. Consequently, further investigations are necessary to obtain a better understanding of the different mixing mechanisms taking place at different spatial length scales to optimize chemical processes and reactor design. Due to the complexity of mixing reactor design, a fundamental flow, such as that associated with a vortex ring, has been selected to develop a reliable procedure to gain some improved understanding of mixing mechanisms by assessing the competitive actions of the strain rate tensor and vorticity vector.

Bourgeois, N., Choroba, P. and Winckelmans, G.

"CONDITIONAL REDUCTION OF ICAO WAKE TURBULENCE SEPARATION MINIMA ON FINAL APPROACH"

5th International Conference on Research in Air Transportation, May 2012, Berkeley, CA.

An intensive LIDAR measurement campaign of aircraft wake vortices (WV) in the landing phase has been carried out at London Heathrow Airport. The WV trajectory and circulation as well as wind intensities have been collected. The possibility of reducing current ICAO wake turbulence minimum separations in case of favorable wind conditions is assessed by comparing the wake vortex encounter (WVE) risk associated to calm conditions to the WVE risk in these propitious conditions. An original approach used to quantify the frequency and the severity of the potential WVE is presented. As some of the WV are stopped being tracked before they effectively become insignificant, it is also decided to fit and extrapolate each WV circulation evolution using a two-phase decay model. First, the computed severity-frequency curves provide generic results, and indicate that a 0.5 NM reduction is possible in case of 'pure' headwind equal to 9-10 knots and 'pure' crosswind equal to 7-8 knots. The potential local application of these conditional reductions is also evaluated at two European hubs, London Heathrow and Paris Charles de Gaulle. The resulting headwind and crosswind thresholds are very similar to those obtained for the generic analysis. Yet, in addition to this theoretical study, a complete safety assessment must be performed before such thresholds can be used operationally to reduce separation.

Bourne, K., Manovski, P., Reddy, K. R. and Ooi, A.

"EXPERIMENTAL EVALUATION OF THE EFFECT OF FLOW DEFLECTORS ON HELICOPTER ROTOR WAKE VORTICES"

18th Australasian Fluid Mechanics Conference, December 2012, Launceston, Australia.

Understanding the rotor wake flow characteristics of a helicopter is fundamental to the investigation of its aerodynamic characteristics. When operating close to the ground the rotor wake can reflect to create large, doughnut-shaped vortices around the helicopter. In certain environments these vortices can cause the formation of dust clouds, resulting in a phenomenon commonly referred to as brownout. This study seeks to assess the interactional aerodynamics between a small-scale rotor wake and a range of active and passive flow deflectors. Two sets of experimental results will be presented, the first a

smoke flow visualization which qualitatively assessed the potential of both passive and active deflectors to modify major wake structures. The second experiment used Particle Image Velocimetry to assess the effect of the active deflectors.

Bourne, K., Wahono, S. and Ooi, A.

"NUMERICAL INVESTIGATION OF VORTEX RING GROUND PLANE INTERACTIONS"

Journal of Fluids Engineering, Vol. 139, July 2017, pp. 071105-1 - 071105-10.

The interaction between multiple laminar thin vortex rings and solid surfaces was studied numerically to investigate flow patterns associated with near-wall flow structures. In this study, the vortex-wall interaction was used to investigate the tendency of the flow toward recirculatory behavior and to assess the near-wall flow conditions. The numerical model shows very good agreement with previous studies of single vortex rings for the case of orthogonal impact (angle of incidence, 0 deg) and oblique impact (20 deg). The study was conducted at Reynolds numbers 585 and 1170, based on the vortex ring radius and convection velocity. The case of two vortex rings was also investigated, with particular focus on the interaction of vortex structures post impact. Compared to the impact of a single ring with the wall, the interaction between two vortex rings and a solid surface resulted in a more highly energized boundary layer at the wall and merging of vortex structures. The azimuthal variation in the vortical structures yielded flow conditions at the wall likely to promote agitation of ground-based particles.

Boutier, A., Lefevre, F. and Micheli, F.

"ANALYSIS OF HELICOPTER BLADE VORTEX STRUCTURE BY LASER VELOCIMETRY"

Experiments in Fluids, Vol. 21, 1996, pp. 33-42

In descent flight, helicopter external noise is mainly generated by the Blade Vortex Interaction (BVI). To understand the dynamics of this phenomenon, the vortex must be characterized before its interaction with the blade, which means that its viscous core radius, its strength, and its distance to the blade have to be determined by non-intrusive measurement techniques. As part of the HART program (Higher Harmonic Control Aeroacoustic Rotor Test, jointly conducted by US Army, NASA, DLR, DNW and ONERA), a series of tests have been made in the German Dutch Wind Tunnel (DNW) on a helicopter rotor with 2 m long blades, rotating at 1040 rpm; several flight configurations, with an advance ratio of 0.15 and a shaft angle of 5.3 degrees, have been studied with different higher harmonic blade pitch angles superposed on the conventional one (corresponding to the baseline case). The flow on the retreating side has been analyzed with a specially designed 3D laser velocimeter, and, simultaneously, the blade tip attitude has been determined to get the blade-vortex miss distance, which is a crucial parameter in the noise reduction. A 3D laser velocimeter, in backscatter mode with a working distance of 5 m, was installed on a platform 9 m high, and flow seeding with submicron incense smoke was achieved in the settling chamber using a remotely controlled displacement device. Acquisition of instantaneous velocity vectors by an IFA 750 yielded mean velocity and turbulence maps across the

vortex as well as the vortex position, intensity, and viscous radius. The blade tip attitude (altitude, jitter, angle of incidence) was recorded by the TART method (Target Attitude in Real Time) which makes use of a CCD camera on which is formed the image of two retroreflecting targets attached to the blade tip and lighted by a flash lamp. In addition to the mean values of the aforementioned quantities, spectra of their fluctuations have been established up to 8 Hz.

Boutier, A., Lefevre, J. and Micheli, F.

"VORTEX INVESTIGATION ON A RETREATING HELICOPTER BLADE WITH 3D LASER VELOCIMETRY IN DNW"

8th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 1996

As part of the HART program (Higher Harmonic Control Aeroacoustic Rotor Test), a series of tests have been made in the German Dutch Wind Tunnel on a helicopter rotor with 2 m long blades, rotating at 1040 rpm; several flight configurations, with an advance ratio of 0.15 and a shaft angle of 5.3 deg, have been studied with different higher harmonic blade pitch angles superposed on the conventional one. Helicopter external noise is mainly generated by the blade vortex interaction; therefore, the vortex must be characterized as to viscous core radius, strength, and distance to the blade by nonintrusive measurement techniques. The flow on the retreating side has been analyzed with a 3D laser velocimeter, and, simultaneously, the blade tip attitude has been determined to get the blade-vortex miss distance, which is a crucial parameter in noise reduction. The blade tip attitude (altitude, jitter, angle of incidence) was recorded via Target Attitude in Real Time, which makes use of a CCD camera on which is formed the image of two retroreflecting targets attached to the blade tip and lighted by a flash lamp. In addition to the mean values of the aforementioned quantities, spectra of their fluctuations have been established up to 8 Hz.

Bower, D. R. and O'Callaghan, J.

"UTILIZATION OF CFD IN THE AMERICAN AIRLINES FLIGHT 587 ACCIDENT INVESTIGATION"

AIAA Paper No. 2008-6905, Honolulu, HI, August 2008

On November 12, 2001, American Airlines flight 587, an Airbus Industrie A300-600, was destroyed when it crashed into the residential area of Belle Harbor, New York, shortly after takeoff from runway 31L at John F. Kennedy International Airport. The NTSB determined that the probable cause of the accident was the in-flight separation of the vertical stabilizer because of the loads beyond ultimate design that were created by the first officer's unnecessary and excessive rudder pedal inputs. During the investigation, it was determined that the airplane had encountered wake turbulence from a Boeing 747 at the time the first officer made his rudder pedal inputs. This paper describes an overview of how the airplane motion and aerodynamic loads on the vertical tail during the accident sequence were determined from the Flight Data Recorder and the aerodynamic properties of the vertical stabilizer and rudder were computed using Computational Fluid Dynamics.

Boyd, E. A. and Kusmarwanto, I.

"GROUND EFFECT ON A ROTOR WAKE"

Report 8323, August 1983, Cranfield Institute of Technology, Cranfield, Bedford, UK.

This paper reports an experimental study of the ground effect on a rotor wake when the rotor is operating at a height of less than one rotor diameter above the ground. Particular attention was paid to how the rotor slipstream reacts to the oncoming wind and to the ground vortex generated when the wake eventually strikes the ground. The rotor wake was visualized by smoke, the ground vortex by a tuft grid and smoke and the ground interaction boundary by a surface flow visualization. An attempt was made to measure the strength of the ground vortex using pitot and static tubes fine enough to cause little disturbance to the vortex field. Details are given of a new rig planned to extend the reported measurements.

Bradley, R. G. and Wray, W. O.

"A CONCEPTUAL STUDY OF LEADING-EDGE-VORTEX ENHANCEMENT BY BLOWING"

Journal of Aircraft, Vol. 11, No. 1, January 1974, pp. 33-38

A conceptual wind-tunnel-test program has been conducted to verify that blowing a stream of high-pressure air over a swept-wing surface in a direction roughly parallel to the leading edge enhances the vortex system. The blowing is shown to intensify the leading-edge vortex and thus delay the deleterious effects of vortex breakdown to higher angle of attack. As a result, the vortex-lift is significantly increased and, as the blowing rate is increased, appears to approach the value predicted by the Polhamus suction-analogy for thin wings.

Bradley, S.

"A SIMPLE MODEL FOR CORRECTING SODAR AND LIDAR ERRORS IN COMPLEX TERRAIN"

Journal of Atmospheric and Oceanic Technology, Vol. 29, December 2012, pp. 1717-1722.

Ground-based sensing of wind profiles by sodars and lidars is becoming the standard for wind energy and other applications. However, there remain difficulties in complex terrain since the instruments sense wind components in spatially separated volumes, and systematic spatial variations of the wind components can lead to systematic bias in wind estimates. The errors are typically less than 6 percent, so corrections do not need to be very sophisticated. Analytic potential flow models are developed for the flow over a bell-shaped hill and over an escarpment. These models are then used to find the radial Doppler shift from sampling volumes in typical sodar and lidar beam geometries, thereby allowing spatial variation bias to be removed. Since the models are straightforward, bias removal is readily achieved, and lends itself to an understanding of the significant parameters affecting wind errors. The bell model is tested against field data from sodars and lidars in both moderately complex and in very

complex terrain. It is found that corrected winds are to within approximately 1 percent of those measured by mast instruments. Much more complex models do not correct wind errors better than these simple models.

Bradley, S. and Mikkelsen, T.

"A REVIEW OF SODAR ACCURACY"

16th International Symposium for the Advancement of Boundary-Layer Remote Sensing, ISARS 2012, June 2012, Boulder, CO.

What accuracy and reliability can today be expected from SODAR wind measurements? Is there traceable evidence for performance? Environmental factors, turbulent fluctuations, and non-uniform terrain all affect the wind speed uncertainty. So, site-to-site variations for SODAR-mast comparisons can be large. On a uniform terrain site, differences between a SODAR and a mast-mounted cup anemometer will arise due to turbulent fluctuations and wind components being measured in different spaces, as well as to variable background noise. We develop theories for turbulence-related random fluctuations due to finite sampling rates and to sampling from spatially distributed volumes. Effects can be minimized by selecting the environment and selectively filtering the data for periods of low fluctuations. But there is still real difficulty in answering the question: How good is a SODAR? Most field use, away from an idealized test environment, appears to produce SODAR-mast rms differences greater than the 0.1 m/s or less typically quoted by SODAR manufacturers. However, in these real environments it is likely that much of the difference arises from the mast sensors and the SODAR measuring in different spaces. We show some field results which reinforce this view. Both the turbulence-related random fluctuations and systematic errors in complex terrain (where systematic wind shears arise) can potentially be removed by use of a vertical column geometry. Field results from a new bistatic receiver shed some light on the differences between such 'common volume' sampling and the usual monostatic sampling.

Bradley, S. G.

"VALIDATION OF SODAR REAL-TIME SENSING AND VISUALISATION OF WAKE VORTICES"

Proceedings of the Twelfth Conference on Aviation Range and Aerospace Meteorology, American Meteorological Society, Atlanta, Georgia, Feb. 2006

We have described the main sources of noise leading to uncertainties in SODAR wind speed estimates. The most common and persistent of these is background acoustic noise. Based on a robust method for estimation of the position of the spectral peak in the SODAR Doppler spectrum, we simulate noisy spectra typical of SODAR data which might arise from observations of aircraft vortices. This field of noisy vertical velocity estimates is used as the input to the inversion method described by Bradley et al. (2006a). The resulting error estimates for the vortex position and strength are shown to depend systematically on SODAR SNR, and on the SODAR array configuration (spacing and number of

SODARs as well as range-gate size). The outcome provides recommendations as to optimized design of a SODAR array for characterization of aircraft vortices.

Bradley, S. G., von Hunerbein, S. and Underwood, K.

"OPERATIONAL RELIABILITY AND ACCURACY OF SODARS IN WING VORTEX CHARACTERIZATION"

Proceedings of the Twelfth Conference on Aviation Range and Aerospace Meteorology, American Meteorological Society, Atlanta, Georgia, Feb. 2006

We have evaluated the common causes of data loss in SODARs: low back-scatter; rainfall; and high background acoustic noise. Contrary to intuition, high background acoustic noise is not expected to be particularly problematic at airports. This finding is supported by measurement experience at many airports. Low back-scatter, due to low thermal or refractive index contrast, has been found to be a major cause of data loss in other field experiments, particularly at elevated heights. However, the vortex situation is rather different in three aspects: 1) most interest is in heights from 0-100 m, 2) airports are high thermal contrast sites, and 3) vortices provide mechanical mixing. These factors are expected to strongly increase data availability. Acoustic back-scatter from rainfall is expected to be the main cause of data loss.

Bradley, S., Mursch-Radlgruber, E. and von Hunerbein, S.

"SODAR MEASUREMENTS OF WING VORTEX STRENGTH AND POSITION"

Journal of Atmospheric and Oceanic Technology, Vol. 24, Feb. 2007, pp. 141-155

A method is developed for robust real-time visualization of aircraft vortex spatial and temporal development based on measurement data from a line array of sodars. The method relies on using a potential-flow vortex model, with spatial averaging according to the along-beam and transverse spatial resolution of the sodar. The model comprises the wing vortex pair, together with two image vortices below ground such that there is no flow through the ground surface. An analytic solution for the temporal-spatial evolution of this four-vortex system is obtained as an aid to establishing relevant scales and performance criteria for any sodar. Field results from an array of four sodars are used on an individual profile basis (every 2 s of real time) to fit the model parameters of vortex circulation, position, and spacing. This method gives vortex trajectories and strength as a function of real time without dependence on assumptions regarding interactions with the atmosphere. Estimates of parameter uncertainties are also produced in real time, and it is found that estimates of position and spacing can be obtained to around plus or minus 4 m and of vortex circulation to plus or minus 50 meters squared per second. Recommendations are given for optimizing sodars for vortex measurement using practical technology.

Brailovskaia, I. I.

"FLOW IN THE NEAR WAKE"

Soviet Physics - Doklady, Vol. 16, Sept. 1971, pp. 197-199.

A numerical solution of Navier-Stokes equations for a compressible viscous gas is obtained in the near-wake region behind the perpendicular (to the flow surface) trailing face of a plate in supersonic flow. The velocity, density, temperature, and boundary layer parameters for the oncoming flow are known. The Navier-Stokes equations for the region of interest consist of two equations of motion, an energy equation, and a continuity equation. Pressure, density, and temperature are related by the equation of state. The viscosity and thermal conductivity coefficients are power functions of temperature. The boundary value problem for the region with specified boundary conditions was solved numerically by the finite difference method. The results for nine different cases of specified initial parameters are given graphically in the form of characteristic streamlines and pressure profiles.

Bramesfeld, G.

"A HIGHER ORDER VORTEX-LATTICE METHOD WITH A FORCE-FREE WAKE"

PhD Thesis, August 2006, The Pennsylvania State University, University Park, PA.

A higher-order, lifting surface method is presented that uses elements with distributed vorticity. Consequently, the newly developed method is highly accurate in force prediction and numerically extremely robust, even when using a relaxed wake model. The accurate prediction is accomplished using lower panel densities than other methods require. The numerical robustness is achieved without compromising the irrotationality assumption, unlike other potential flow methods do that use discrete vortices with solid core models in the wake. The distributed vorticity element of the newly developed method consists of a vortex sheet that holds streamwise vorticity that varies linearly over the element span. Transverse vorticity is concentrated in two vortex filaments that are located along the leading and trailing edge of the element. Their spanwise circulation distributions vary in a parabolic fashion. The circulations of the leading and trailing edge filaments are equal in magnitude, but opposite in orientations. By introducing additional singularities along the edges of the distributed vorticity elements, any extreme velocities associated with the edge singularities of the vortex sheets are removed. The velocity induced by a distributed vorticity element is determined with an analytical expression. One of several spanwise systems of distributed vorticity elements are used to model the lifting surface and the wake that is relaxed using a time-stepping method. There, the shed vorticity forms an essentially continuous vortex sheet. Thus, because of the elimination of point or line singularities, many of the numerical problems are avoided that are encountered with conventional vortex-lattice and panel methods. In addition, the continuous vorticity distribution across the lifting surface yields an accurate load prediction that is relatively insensitive to panel density changes on the lifting surface and in the wake. Consequently, significantly fewer singularity elements are needed to achieve accuracies comparable to other potential flow methods. The subsequent method is a relatively fast tool for determining the location of the free wake and its interaction with complex wing geometries, especially when accurate load predictions are required. The potential of the method is demonstrated with two sample applications. Especially in the case of the formation flight of two aircraft, the relaxed wake model yields performance results that differ to those that are obtained with a fixed wake model.

Bramesfeld, G. and Maughmer, M. D.

"EFFECTS OF WAKE ROLLUP ON FORMATION-FLIGHT AERODYNAMICS"

J. Aircraft, Vol. 45, No. 4, July-August 2008, pp. 1167-1173

The aerodynamic performance of two high aspect-ratio wings flying in formation is investigated with particular interest in the importance of considering wake rollup in making aerodynamic predictions. For this purpose, formations of various separations were investigated using a drag-free, fixed-wake model as well as a force-free, relaxed one. In all cases the aircraft were trimmed for roll and the follower aircraft pitch attitude was adjusted to match the lift coefficient of the lead aircraft. Both wake representations result in similar induced-drag minima for the follower aircraft which result when the lateral overlaps of the two aircraft are around 10 percent of a wingspan. Computations with the fixed-wake model, however, predict a wider region of lateral separations having the lowest induced drag than do the simulations with wake rollup. A small performance difference due to the model also exists when one aircraft follows directly behind the other. Independent of the wake model used, trimming the aircraft in roll and pitch can have a significant influence on their performance, although the required control-input solutions for trim are essentially not affected by the choice of wake representation.

Bramesfeld, G. and Maughmer, M. D.

"RELAXED-WAKE VORTEX-LATTICE METHOD USING DISTRIBUTED VORTICITY ELEMENTS"

J. Aircraft, Vol. 45, No. 2, March-April 2008, pp. 560-568

A lifting-surface method is presented that uses elements having distributed vorticity to model lifting surfaces and their shed wakes. Using such distributed vorticity elements allows the representation of a force-free continuous wake-vortex sheet that is free of numerical singularities and is thus robust in its numerical rollup behavior. Unlike other potential-flow methods that use discrete vortex filaments having solid-core models at their centers to avoid problems with the singularities, the numerical robustness of the new method is achieved without the subsequent solution being dependent on the choice of a cutoff distance or core size. The computed loads compare well with the results of classical theory and other potential-flow methods. Its numerical robustness, computational speed, and ability to predict loads depend strongly on the influence of the wake and its shape, as is the case for the two application examples presented: formation flight and rotating-wing systems.

Bramesfeld, G. and Maughmer, M. D.

"THE EFFECTS ON FORMATION-FLIGHT AERODYNAMICS DUE TO WAKE ROLLUP"

AIAA Paper No. 2007-729, Reno, NV, January 2007

A lifting-surface method is used to investigate the aerodynamic performance of two high aspect-ratio wings flying in formation. In particular, the influence of wake rollup is investigated. The relaxed-wake

cases have performance results that differ from those obtained with a fixed-wake model. In particular, the fixed-wake model predicts more optimistic results for the follower aircraft for formations having a lateral separation of 70- to 90-percent span, which are also the lateral formation spacings with the greatest performance gains for the trailing aircraft. For formations with streamwise separations of a half-span or more, the choice of wake model has very little influence on the changes resulting from the formation moving further apart in the streamwise direction. This reflects the fact that, in the case of the relaxed wake, most of the rollup of the lead-aircraft wake occurs within a short distance aft of its trailing edge and any further wake-roll-up has little effect. In contrast, the fixed wake model experiences no changes at all after being shed. Increasing lateral and vertical separations reduce the differences due to a fixed versus relaxed wake. For the investigation of the performance of the formation, both aircraft are trimmed in pitch and roll. To a limited degree, the control inputs required to trim the formation depend on whether the relaxed- or fixed wake model is used, especially when the performance of the trailing aircraft is at an optimum.

Brand, A., Komerath, N. and McMahon, H.

"RESULTS FROM LASER SHEET VISUALIZATION OF A PERIODIC ROTOR WAKE"

J. Aircraft, Vol. 26, No. 5, May 1989, pp. 438-443

A laser sheet has been applied to the visualization of a periodic rotor wake produced by a model rotorcraft in forward flight. A stiff, two-bladed teetering rotor is mounted independently of an idealized airframe consisting of an instrumented circular cylinder with a hemispherical nose. The model was installed in a wind tunnel, and tests were carried out at three different advance ratios (forward flight speeds) at one value of rotor collective pitch angle. The laser sheet technique enables detailed flow visualization to be carried out. Quantitative data regarding the location of the rotor tip vortex can be obtained. Results from the flow visualization confirm that the rotor wake is a complex flow field not amenable to simple analysis. However, the details of the tip vortex geometry are both periodic and repeatable. The motion of the rotor wake near the airframe is examined. The behavior of the tip vortex is strongly affected by the presence of the airframe. In particular, the interaction of the rotor tip vortex with the airframe results in the destruction of the vortex core; apparently the vorticity is diffused, and the vortex loses its definition. No vortex filaments appear below the airframe as identifiable flow features. Examples of airframe surface pressure data are presented and are seen to correlate well with the results from the flow visualization.

Brandon, J. M., Jordan, Jr., F. L., Buttrill, C. W. and Stuever, R. A.

"APPLICATION OF WIND TUNNEL FREE-FLIGHT TECHNIQUE FOR WAKE VORTEX ENCOUNTERS"

NASA TP-3672, November 1997, Langley Research Center, Hampton, VA

A wind tunnel investigation was conducted in the Langley 30- by 60-Foot Tunnel to access the free-flight test technique as a tool in research on wake vortex encounters. A typical 17.5-percent scale business-class jet airplane model was flown behind a stationary wing mounted in the forward portion

of the wind tunnel test section. The span ratio (model span-generating wingspan) was 0.75. The wing angle of attack could be adjusted to produce a vortex of desired strength. The test airplane model was successfully flown in the vortex and through the vortex for a range of vortex strengths. Data obtained included the model airplane body axis accelerations, angular rates, attitudes, and control positions as a function of vortex strength and relative position. Pilot comments and video records were also recorded during the vortex encounters.

Brandt, L. and Nomura, K. K.

"THE PHYSICS OF VORTEX MERGER AND THE EFFECTS OF AMBIENT STABLE STRATIFICATION"

J. Fluid Mech., Vol. 592, 2007, pp. 413-446

The merging of a pair of symmetric, horizontally oriented vortices in unstratified and stably stratified viscous fluid is investigated. Two-dimensional numerical simulations are performed for a range of flow conditions. The merging process is resolved into four phases of development and key underlying physics are identified. In particular, the deformation of the vortices, explained in terms of the interaction of vorticity gradient, and rate of strain leads to a tilt in vorticity contours in the vicinity of the center of rotation (a hyperbolic point). In the diffusive/deformation phase, diffusion of the vortices establishes the interaction between the vorticity gradient and mutually induced rate of strain. During the convective/deformation phase, induced flow by filaments and, in stratified flow, baroclinically generated vorticity (BV), advects the vortices thereby modifying rate of strain, which, in general, may enhance or hinder the development of the tilt. The tilting and diffusion of vorticity near the center hyperbolic point causes vorticity from the core region to enter the exchange band where it is entrained. In the convective/entrainment phase, the vortex cores are thereby eroded and ultimately entrained into the exchange band, whose induced flow becomes dominant and transforms the flow into a single vortex. The critical aspect ratio, associated with the start of the convective/entrainment phase, is found to be the same for both the unstratified and stratified flows. In the final diffusive/axisymmetrization phase, the flow evolves towards axisymmetry by diffusion. In general, the effects of stratification depend on the ratio of the diffusive time scale (growth of cores) to the turnover time (establishment of BV), i.e. the Reynolds number. A crossover Reynolds number is found, above which convective merging is accelerated with respect to unstratified flow and below which it is delayed.

Brandt, L. K.

"NUMERICAL AND ANALYTICAL STUDIES OF TWO-DIMENSIONAL VORTEX PAIR DYNAMICS IN UNSTRATIFIED AND STRATIFIED ENVIRONMENTS"

PhD Thesis, 2009, University of California, San Diego, CA.

This work investigates fundamental two-dimensional vortex pair dynamics in unstratified and stably stratified environments through numerical and analytical techniques. The study focuses on two main topics: (i) vortex interaction and merging of co-rotating vortex pairs and (ii) internal wave generation by co-rotating and counter-rotating vortex pairs. Two-dimensional vortex merging in a viscous fluid is

studied using numerical simulations. Analysis of the ideal case of two equal co-rotating vortices (symmetric pair) identifies the basic underlying physics of vortex merger. Through the interaction of the vorticity gradient and the mutually induced strain rate near the central hyperbolic point, a tilt in vorticity contours is established. This leads to core detrainment and the entrainment of core fluid into the exchange band, which transforms the flow into a single vortex. In the case of the asymmetric (unequal strength) vortex pair, the disparity in the deformation rates between the vortices alters the interaction. A critical value for a strain rate parameter characterizing the establishment of core detrainment is determined. The onset of merging is associated with the achievement of the critical strain by both vortices and a generalized merging criterion is formulated. The generation of internal waves by horizontally oriented co-rotating and counter-rotating vortex pairs is studied. Linearized inviscid equations are derived that describe the internal wave, vorticity, and energy fields. These solutions are compared with nonlinear numerical viscous simulations in moderately and strongly stratified environments. Through evaluation of the energy field, the time at which the flow reaches a steady state for strongly stratified flows is found, along with a characterization of the regimes of strongly and moderately stratified environments.

Brandt, L. K. and Nomura, K. K.

"CHARACTERIZATION OF THE INTERACTION OF TWO UNEQUAL CO-ROTATING VORTICES"

Journal of Fluid Mechanics, Vol. 646, 2010, pp. 233-253.

The interactions and merging of two unequal co-rotating vortices in a viscous fluid are investigated. Two-dimensional numerical simulations of initially equal-sized vortices with differing relative strengths are performed. In the case of equal-strength vortices, i.e. symmetric vortex pairs, the mutually induced strain deforms and tilts the vortices, which leads to a core detrainment process. The weakened vortices are mutually entrained and rapidly move towards each other as they intertwine and destruct. The flow thereby develops into a single compound vortex. With unequal strengths, i.e. asymmetric pairs, the disparity of the vortices alters the interaction. Merger may result from reciprocal but unequal entrainment, which yields a compound vortex; however other outcomes are possible. The various interactions are classified based on the relative timing of core detrainment and core destruction of the vortices. Through scaling analysis and simulation results, a critical strain rate parameter which characterizes the establishment of core detrainment is identified and determined. The onset of merging is associated with the achievement of the critical strain rate by 'both' vortices, and a merging criterion is thereby developed. In the case of symmetric pairs, the critical strain rate parameter is shown to be related to the critical aspect ratio. In contrast with symmetric merger, which is in essence a flow transformation, asymmetric merger may result in the domination of the stronger vortex because of the unequal deformation rates. If the disparity of the vortex strengths is sufficiently large, the critical strain rate is not attained by the stronger vortex before destruction of the weaker vortex, and the vortices do not merge.

Brandt, L. K., Cichocki, T. K. and Nomura, K. K.

"ASYMMETRIC VORTEX MERGER: MECHANISM AND CRITERION"

Theoretical Computational Fluid Dynamics, Vol. 24, 2010, pp. 163-167.

The merging of two unequal co-rotating vortices in a viscous fluid is investigated. Two-dimensional numerical simulations of initially equal sized Lamb-Oseen vortices with differing relative strengths are performed. Results show how the disparity in deformation rates between the vortices alters the interaction. Key physical mechanisms associated with vortex merging are identified. A merging criterion is formulated in terms of the relative timing of core detrainment and destruction. A critical strain parameter is defined to characterize the establishment of core detrainment. This parameter is shown to be directly related to the critical aspect ratio in the case of symmetric merger.

Brandt, R.

"DRAG EVALUATION BY WAKE SURVEY"

Stagiaire Report 1988-31, September 1988, von Karman Institute for Fluid Dynamics, Waterloo, Belgium.

A computer program that calculates the drag of a body placed in a wind-tunnel is modified so the drag can be calculated by a single traverse plane downstream of the body. The results are compared with direct measurement of the forces by using an aerodynamic balance.

Brandt, S. A.

"VORTEX BURST MODEL FOR THE VORTEX LATTICE METHOD"

Journal of Aircraft, Vol. 32, No. 6, November-December 1995, pp. 1394-1396.

A model for leading-edge vortex bursting has been developed and used with the vortex lattice method to predict vortex bursting on highly swept wings. The model was derived from the steady, incompressible Navier-Stokes equations for the vortex core. The method was tested on four highly swept wing models. In all cases vortex burst predictions agreed well with the vortex burst locations observed in wind- and water-tunnel tests.

Brandt, S. A. and Iversen, J. D.

"MERGING OF AIRCRAFT TRAILING VORTICES"

Journal of Aircraft, Vol. 14, No. 12, December 1977, pp. 1212-1220

A merging distance criterion for equal-strength corotational vortices is derived from low-turbulence wind tunnel flow visualization data. The vortex separation distance is normalized by defining a vortex core diameter based on circulation defect and angular momentum defect. Merging may take place for larger separation distances than predicted from earlier two-dimensional inviscid calculations, which

indicates that viscosity and possibly three-dimensional effects are important factors in the merging phenomenon. Hot-wire velocity distributions and rolling moment measurements show that attenuation of the vortex hazard is associated with vortex merging.

Branstetter, J. R., Hastings, E. C. and Patterson, J. C.

"FLIGHT TEST TO DETERMINE FEASIBILITY OF A PROPOSED AIRBORNE WAKE VORTEX DETECTION CONCEPT"

NASA-TM-102672, DOT/FAA/CT-TN-90/25, April 1991, NASA Langley Research Center, Hampton, VA

An investigation was conducted jointly by the FAA and NASA to determine the radial extent of the circulatory flow field around the lift-induced vortex system of an aircraft in flight. This flow field, if found to be of sufficient strength and span to activate instrumentation onboard a following aircraft, may provide the basis for designing a feasible airborne wake detection and avoidance system. A small probe aircraft was flown behind a larger wake generator aircraft to measure the lateral separation distance at which the vortex could be detected using conventional instrumentation. This report discusses the results and mechanics of the flight test and proposes recommendations for future tests.

Brasefield, C. J.

"WINDS AND TEMPERATURES IN THE LOWER STRATOSPHERE"

Journal of Meteorology, Vol. 7, February 1950, pp. 66-69.

About twenty radiosonde flights to altitudes above 100,000 ft have been made from Belmar, New Jersey (latitude 40.2 degrees N) during the period July 1948 to April 1949, using a balloon whose nominal weight was 10,000 grams. The radiosonde and associated equipment were specially designed to accurately measure pressure, temperature, and winds to an altitude of 150,000 ft. It was found that the mean daytime temperature of the stratosphere is about -60C from 50,000 ft to 60,000 ft, above which the mean temperature rises at a rate of about 0.5C per 1000 ft to a temperature of about -30C at 120,000 ft. No abnormally high temperatures at high altitudes resulting, for example, from a solar flare, were detected in any of these flights.

Brashears, M. R. and Eberle, W. R.

"VERIFICATION OF WIND MEASUREMENT TO 450-METER ALTITUDE WITH MOBILE LASER DOPPLER SYSTEM"

FAA-RD-77-181, December 1977, Lockheed Missiles & Space Co., Huntsville, AL.

The Lockheed mobile atmospheric unit is a laser Doppler velocimeter system designed for the remote sensing of winds. The capability of the laser Doppler velocimeter accurately to measure winds to 150-meter altitude has been previously demonstrated. To assess the capability of the laser Doppler velocimeter to measure winds at higher altitudes, the system was tested adjacent to the 481-meter

instrumented WKY-TV television transmission tower at the National Severe Storms Laboratory test site near Norman, Oklahoma. Comparisons between the laser-measured winds and the anemometer-measured winds are presented. The sources of discrepancies between laser-measured and anemometer-measured wind are discussed.

Brashears, M. R. and Hallock, J. N.

"AIRCRAFT WAKE VORTEX TRANSPORT MODEL"

Journal of Aircraft, Vol. 11, No. 5, May 1974, pp. 265-272

A wake vortex transport model has been developed which includes the effects of wind and wind shear, buoyancy, mutual and self-induction, ground plane interaction, viscous decay, finite core and Crow instability effects. Photographic and ground-wind vortex tracks obtained from DC-6, B-747, B-707, and CV-880 aircraft flybys are compared with predicted vortex tracks computed using meteorological and aircraft data as inputs to the transport model. A parametric analysis of the effects of the aircraft, fluid mechanic, and meteorological parameters shows the relative magnitude of each transport mechanism. The study constitutes the first detailed comparison of vortex transport theory with experimental data.

Brashears, M. R. and Hallock, J. N.

"ANALYSIS OF PREDICTED AIRCRAFT WAKE VORTEX TRANSPORT AND COMPARISON WITH EXPERIMENT"

Journal of Aircraft, Vol. 12, No. 7, July 1975, pp. 619-620

An aircraft wake vortex transport model has been developed which combines fluid mechanic representations of the various vortex-induced and atmospheric effects. A series of flight tests was conducted to verify the model using B-747, B-707, CV-880 and DC-6 aircraft in which both the motion of the vortices and the attendant meteorological conditions were recorded. The differences between predicted and measured vortex tracks consistently fell within the computed uncertainty in the transport due to random fluctuations in the wind field.

Brashears, M. R. and Hallock, J. N.

"PREDICTIVE MOTION OF WAKE VORTICES"

Proceedings Int. Conf. on Future of Aircraft All-Weather Operations, Inst. Electrical Engineers, London, November 1976, pp. 42-45

Predictive models for the motion of wake vortices are considered as a contribution to vortex avoidance strategy. Four stages are envisaged in the construction of a predictive model: a mathematical model of vortex behavior based on aerodynamics and fluid mechanics; verifying the model against controlled flight test data; refining the model to account for deviations; verification of

the model under operational conditions. Each stage is discussed separately. A geometrical approach to vortex detrainment in an approach zone with wind velocity considered is sketched.

Brashears, M. R. and Hallock, J. N.

"THE MEASUREMENT OF WIND SHEAR AND WAKE VORTICES BY LASER VELOCIMETRY"

Proceedings 7th Conf. on Aerospace and Aeronautical Meteorology, AIAA/AMS, Melbourne, FL, November 1976, pp. 175-181

The Laser Doppler Velocimeter (LDV) discussed was developed to measure three-dimensional wind and corresponding wind shear at heights below 500 m, and the location and persistence of aircraft wake vortices in the terminal environment. In particular, the Vertical Azimuth Display mode of operation is shown to be an extremely accurate technique. The measurement accuracy of + or -0.5 m/sec in wind speed and + or - 2.5 deg in wind direction has been further improved by using least-squares techniques in data processing.

Brashears, M. R. and Hallock, J. N.

"A PREDICTIVE MODEL OF WAKE VORTEX TRANSPORT"

Proceedings of the Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorological Society, 1974, pp. 387-392

An aircraft wake vortex transport model has been developed which includes meteorological and fluid mechanic mechanisms. It has been applied to the prediction of the location of aircraft vortices relative to an approach corridor; comparisons of predicted tracks with measured vortex tracks show excellent agreement. The effects of wind shear and the Ekman spiral on vortex transport are discussed, and it is shown that the combination of wind shear and ground effect may be possible mechanisms underlying the tilting of vortices. The application of Pasquill class criteria is shown to be an effective technique to describe the wind profile in the absence of detailed wind data.

Brashears, M. R. and Zalay, A. D.

"LASER DOPPLER VELOCIMETER MEASUREMENTS OF B-747 WAKE VORTEX CHARACTERISTICS"

FAA-RD-77-85, September 1977, Lockheed Missiles & Space Company, Huntsville, AL

To determine the behavior of the wake vortices of a B-747 at low altitudes and to measure the vortex-decay process behind the B-747 as a function of altitude above ground, flap and spoiler settings, and different flight configurations, a B-747 aircraft flew 54 passes at low level over a ground-based laser Doppler velocimeter (LDV) system. From the LDV measurements, the location and flow field of the wake vortices and the general vortex roll-up, transport, and decay trends were obtained. Results of the study indicated that the deployment of spoilers and flaps enhanced the decay of the vortex peak tangential velocity in the near wake while aircraft altitude, glide slope, and landing gear deployment

had little effect. The report discusses the LDV wake vortex measurements including the instrumentation used, the experimental test sequence, the results of the wake measurements in terms of the vortex roll-up, transport, and decay trends, and a comparison of the wake vortex characteristics for different configurations.

Brashears, M. R., Hallock, J. N. and Logan, N. A.

"ANALYSIS OF PREDICTED AIRCRAFT WAKE VORTEX TRANSPORT AND COMPARISON WITH EXPERIMENT"

AIAA Paper No. 1974-0506, Palo Alto, CA, June 1974.

Predicted vortex tracks from a wake vortex transport model previously developed (including the effects of wind and wind shear, buoyancy, mutual and self-induction, ground plane interaction, viscous decay, and finite core and Crow instability effects) have been compared with vortex tracks obtained from B-747, B-707, CV-880 and DC-6 aircraft flybys. Excellent agreement was found between prediction and measurement when sufficient wind data were available. A detailed explanation of vortex tilting is given along with observations concerning the mechanism itself.

Brashears, M. R., Lawrence, T. R. and Zalay, A. D.

"MOBILE LASER DOPPLER SYSTEM CHECKOUT AND CALIBRATION, VOLUME II: APPENDIXES"

FAA-RD-77-48,II, June 1977, Lockheed Missiles & Space Company, Huntsville, AL.

A program has been carried out to make modifications to the Lockheed-Huntsville Mobile Laser Doppler Velocimeter (LDV) system; to calibrate and operate the system at the John F. Kennedy (JFK) Airport; to obtain a data base of wind, wind shear, and wake vortex measurements; and to assess the basic operational capabilities of the system based on these measurements. The basic operational capabilities, resolution, and integrity of a scanning LDV for the remote sensing of winds, wind shear, and wake vortices at terminal areas has been established. Volume I, 150 pages, contains text.

Brashears, M. R., Lawrence, T. R. and Zalay, A. D.

"MOBILE LASER DOPPLER SYSTEM CHECKOUT AND CALIBRATION"

FAA-RD-77-48, June 1977, Lockheed Missiles & Space Co., Huntsville, AL

A program has been carried out to make modifications to the Lockheed-Huntsville Mobile Laser Doppler Velocimeter (LDV) system; to calibrate and operate the system at the John F. Kennedy (JFK) Airport; to obtain a data base of wind, wind shear, and wake vortex measurements; and to assess the basic operational capabilities of the system based on these measurements. The basic operational capabilities, resolution, and integrity of a scanning LDV for the remote sensing of winds, wind shear, and wake vortices at terminal areas has been established.

Brashears, M. R., Logan, N. A. and Hallock, J. N.

"THE EFFECT OF WIND SHEAR AND GROUND PLANE ON AIRCRAFT WAKE VORTICES"

Journal of Aircraft, Vol. 12, No. 10, October 1975, pp. 830-833

A previous comparison of predicted wake vortex transport with experiment revealed two consistent sources of discrepancy, namely, lower predicted sink rates of the vortex pair relative to observed and a lagging of the predicted upwind vortex transport compared with the measured values. It was hypothesized that either a wake tilting or a decrease in circulation was occurring to account for this lagging. Accordingly, an analysis was performed to determine the streamlines associated with the presence of a vortex pair in a shear near the ground and the movement of the stagnation points in such a region. It was found that the upper and lower stagnation points rise or sink relative to their shearless location, depending upon the magnitude of non-dimensional parameters defining ground proximity and wind shear to circulation.

Brashears, M. R., Logan, N. A., Robertson, S. J., Shrider, K. R. and Walters, C. D.

"ANALYSIS OF PREDICTED AIRCRAFT WAKE VORTEX TRANSPORT AND COMPARISON WITH EXPERIMENT"

FAA-RD-74-74.I and 74.II, April 1974, Lockheed Missiles & Space Company, Huntsville, AL

A unifying wake vortex transport model is developed and applied to a wake vortex predictive system concept. The fundamentals of vortex motion underlying the predictive model are discussed including vortex decay, bursting, and instability phenomena. A parametric and sensitivity analysis is presented to establish baseline uncertainties in the algorithm to allow meaningful comparison of predicted and measured vortex tracks. A detailed comparison of predicted vortex tracks with photographic and ground-wind vortex data is presented. Excellent agreement between prediction and measurement is shown to exist when sufficient wind data are available. Application of the Pasquill class criteria is shown to be an effective technique to describe the wind profile in the absence of detailed wind data. The effects of wind shear and the Ekman spiral on vortex transport are discussed. It is shown that the combination of wind shear and ground plane may be possible mechanisms underlying vortex tilting and a theoretical explanation is advanced that is somewhat supported by comparison with the experimental data. Finally, recommendations for further vortex data collection in the vicinity of an airport are presented.

Brashears, M. R., Robertson, S. J., Johnson, B. C., Fan, C. and Shrider, K. R.

"WAKE VORTEX TRANSPORT CONSIDERATIONS AND METEOROLOGICAL DATA ANALYSIS"

LMSC-HREC TR D390424, November 1974, Lockheed Missiles & Space Company, Huntsville, AL

Comparisons were made between predicted wake vortex motions and vortex tracks measured by propeller anemometers arrayed in baselines oriented perpendicularly to the aircraft flight path. The

effect of buoyancy in ground plane on the predicted vortex transport was described. Meteorological data processing computer routines were developed to provide a detailed atmospheric characterization.

Brashears, M. R., Robertson, S. J., Love, D. A., Shrider, K. R. and Zalay, A. D.

"ANALYSIS OF WAKE VORTEX MEASUREMENTS"

LMSC-HREC TR D496558, September 1975, Lockheed Missiles & Space Company, Huntsville, AL

Wake vortex measurements obtained by DOT-TSC at John F. Kennedy (JFK) International Airport have been reduced, analyzed, and correlated with a theoretical vortex transport model. The predictive wake vortex transport model has been updated so that detailed on-site meteorological measurements can be interpreted and utilized to predict more accurately the vortex transport and decay characteristics. A discussion of the wake vortex test data analysis and software development is presented including a description of the JFK wake vortex test program, the computer processing of wake vortex measurements, the analysis of ground wind sensor measurements, and the analysis of meteorological measurements.

Brashears, M. R., Shrider, K. R., Love, D. A., Robertson, S. J. and Zalay, A. D.

"WAKE VORTEX AND GROUNDWIND METEOROLOGICAL MEASUREMENTS"

FAA-RD-76-93, May 1976, Lockheed Missiles & Space Company, Huntsville, AL

Wake vortex ground-wind and meteorological measurements obtained by DOT-TSC at John F. Kennedy (JFK) International Airport have been reduced, analyzed, and correlated with a theoretical vortex transport model. The predictive Wake Vortex Transport Model has been updated so that detailed on-site meteorological measurements can be interpreted and utilized to predict more accurately the vortex transport and decay characteristics. A discussion of the wake vortex test data analysis and software development is presented, including a description of the JFK wake vortex test program, the computer processing of wake vortex measurements, the analysis of ground wind sensor measurements, and the analysis of meteorological measurements.

Brashears, M. R., Zalay, A. D. and Eberle, W. R.

"PREDICTED AND MEASURED WAKE VORTEX MOTION NEAR THE GROUND"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 316-325

Vortex track and meteorological measurements obtained by the Transportation Systems Center at Kennedy International Airport have been processed and cataloged in a computerized data management system. A total of 1320 flybys have been cataloged. A calculated vortex track using meteorological data measured concurrently with the measured vortex track has been generated and placed in the data management system for each flyby. An analysis of measured vortex parameters and corresponding

vortex parameters generated from the analytic model was performed. A comparison of calculated vortex residence time and measured vortex residence time is presented. The reasons for deviations between the calculated residence time and measured residence time are discussed. Design considerations for a wake vortex avoidance system are also discussed.

Brashears, M. R., Zalay, A. D., Chou, L. C. and Shrider, K. R.

"DEVELOPMENT OF PREDICTIVE WAKE VORTEX TRANSPORT MODEL FOR TERMINAL AREA WAKE VORTEX AVOIDANCE"

FAA-RD-76-94, May 1976, Lockheed Missiles & Space Company, Huntsville, AL

The wake vortex transport program has been expanded to include viscous effects and the influence of initial roll-up, atmospheric turbulence, and wind shear on the persistence and motion of wake vortices in terminal areas. Analysis of wake characteristics has shown that changes in the spanwise loading due to flaps increase the initial sink rate, decrease the separation, and initiates the circulation decay process earlier. Buoyancy due to jet exhaust entrainment and ambient stratification retards vortex spreading and increases descent. Atmospheric turbulence and shear promote a more rapid decay reducing the late-time descent and spread rates of vortices. Vortex tilting has been related to an interaction involving the wind shear, ground plane, and the vorticity detrainment process. Recognition of the effects of tilting, spanwise loading, vorticity detrainment, burst/sink instabilities, and atmospheric conditions has resulted in an analytic wake transport and decay model with increased accuracy and improved predictive capabilities.

Brashears, M. R., Zalay, A. D., Hallock, J. N. and Burnham, D. C.

"LASER DOPPLER FLIGHT TEST MEASUREMENTS OF B-747 WAKE VORTEX CHARACTERISTICS"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 106-113

In order to determine the behavior of aircraft wake vortices at low altitudes and to measure the wake vortex decay process behind a wide-body transport aircraft as a function of altitude above ground, flap and spoiler settings, and different flight configurations; a B-747 aircraft flew 54 passes at low level over a ground-based laser-Doppler velocimeter (LDV) system. From the LDV measurements, the location and velocity distribution of the wake vortices and the general vortex roll-up, transport, and decay trends were obtained. Results of the study indicated that the deployment of spoilers and flaps enhanced the decay of the vortex peak tangential velocity in the near wake while aircraft altitude, flight path angle, and landing gear deployment had little effect. The paper discusses the LDV wake vortex measurements including the instrumentation used, the experimental test sequence, and the results of the wake measurements in terms of the vortex rollup, transport and decay trends. A comparison of the wake vortex characteristics for different aircraft configurations is also presented.

Bray, T. P. and Garry, K. P.

"PREDICTION OF THE VORTICITY FIELD PRODUCED BY AIR-JET VORTEX GENERATORS"

ICAS Paper 98-2.8.2, Sept. 1998, Melbourne, Australia.

A parametric study of the vorticity profiles of air-jet vortex generators has been carried out, and an empirical model which allows the prediction of the vorticity field downstream of the air-jet vortex generators has been derived. Measurements were carried out in two studies: a low speed and a high-speed test. The low-speed test was at a free-stream velocity of 20 m/s ($M = 0.588$), while the high-speed test was at Mach numbers of 0.5, 0.6, 0.75. Both tests used a miniature 5-hole pressure probe traversed in a plane normal to the free-stream, downstream of the vortex generators. The experimental data has been used to produce a series of relationships which allow the prediction of vorticity from vortex generators with the aim of simplifying numerical simulations of a flow field incorporating such devices.

Brazier, J.-P.

"SPATIAL STABILITY ANALYSIS OF A FLAP SIDE EDGE VORTEX"

Computational Aeroacoustics: From Acoustic Sources Modeling to Far-Field Radiated Noise Prediction
Colloquium EUROMECH 449, December 9-12, 2003, Chamonix, France

The flap side edge vortex is suspected to contribute to aerodynamic noise generation. Using a temporal stability analysis, Khorrami has shown that unstable modes could exist in this vortex. Due to the convective nature of this instability, a spatial analysis is more suitable. This is the subject of the present work. The mean flow past a 2D wing with a half-span flap has been computed with a steady 3D Navier-Stokes code. Then, local linear stability calculations are performed in several planes perpendicular to the vortex axis. The vortex is assumed axisymmetric and modelled with Batchelor's analytical vortex. Using Gaster's relation, the spatial amplification rate is calculated, giving by integration the relative amplitude of the fluctuations. Some low-frequency fluctuations are seen to be preferentially amplified by the vortex, but the amplifications remain small.

Brazier, J.-P., Moens, F. and Bardoux, P.

"SPATIAL STABILITY ANALYSIS OF A FLAP SIDE EDGE VORTEX"

Aeroacoustics, Vol. 4, Nos. 1 and 2, 2005, pp. 37-47

The flap side edge vortex is suspected to contribute to aerodynamic noise generation. Using a temporal stability analysis, Khorrami and Singer have shown that unstable modes could exist in this vortex. Due to the convective nature of this instability, a spatial analysis is more suitable. This is the subject of the present work. The mean flow past a 2D wing with a half-span flap has been computed with a steady 3D Navier-Stokes code. Then, local linear stability calculations are performed in several planes perpendicular to the vortex axis. The vortex is assumed axisymmetric and modelled with Batchelor's analytical vortex. Using Gaster's relation, the spatial amplification rate is calculated, giving

by integration the relative amplitude of the fluctuations. Some low-frequency fluctuations are seen to be preferentially amplified by the vortex, but the amplifications remain small, so that this mechanism alone should not produce important noise in this particular configuration, where the flap deflection angle is moderate.

Breidenthal, R. E.

"A NEW PARAMETER FOR VORTICES NEAR INTERFACES -- THE VORTEX PERSISTENCE"

AIAA Paper No. 1997-0437, Reno, NV, January 1997

When a turbulent vortex is near an interface such as a solid wall, the fluxes at the interface depend on conventional parameters such as the Reynolds, Schmidt and Prandtl numbers. A new theory asserts that another parameter is equally important. The vortex persistence is a measure of the stationarity of the vortex with respect to the surface. It is defined as the number of rotations the vortex completes while in one place. The persistence is proportional to the ratio of rotational to translational speeds of the vortex, the eddy viscosity ratio. If it is small, then the smallest scale turbulence controls the wall fluxes, the Kolmogorov microscale. On the other hand, if the persistence is large, the largest scale vortices control the fluxes. The theory compares favorably with laboratory experiments of stratified entrainment, wall heat transfer, and starting vortices in the human heart.

Breitsamter, C.

"EXPERIMENTAL AERODYNAMICS APPLIED TO SEPARATED AND VORTICAL FLOWS"

NATO STO, AVT-307, Research Symposium on Separated Flow: Prediction, Measurement and Assessment for Air and Sea Vehicles, October 2019, Trondheim, Norway, paper 16.

An overview of measurement techniques and application scenarios is presented focusing on leading- and trailing-edge vortex flow development. Measurement data obtained for the Mach number range of interest are typically exploited for the analysis of global and local aerodynamic load characteristics as well as for the analysis of flow physics phenomena based on specific field quantities. Experimental data serve as reference data for numerical flow simulations. Today's high fidelity computational simulations require high quality experimental data of detailed flow field quantities to improve numerical schemes and, in particular, to set up and enhance numerical modeling related to transitional and turbulent flow. Similarity in Reynolds number may require cryogenic wind tunnel testing which substantially increases the effort on measurement equipment and test conduction. The present article briefly addresses standard measurement techniques to obtain aerodynamic forces and moments, surface pressures, flow field velocities and surface flow visualization. A special focus is on optical measurement systems including pressure sensitive paint, particle image velocimetry and photogrammetry for surface deformation analysis. Transition detection methods are addressed as well. Future directions concentrate on time-accurate and volumetric measurements enhancing continuously the capabilities of particle image velocimetry applications as well as on refinements of unsteady pressure sensitive paint.

Breitsamter, C.

"WAKE VORTEX CHARACTERISTICS OF TRANSPORT AIRCRAFT"

Progress in Aerospace Sciences, Vol. 47, 2011, pp. 89-134.

The flow and flight physics of wake vortex systems has been intensively investigated concentrating on a large variety of aspects. This paper gives a brief overview on past and present wake vortex research activities such as early studies, integrated programs, model and flight tests, numerical investigations, fundamental physical aspects and alleviation strategies. Then, detailed results of the properties of the wake near field and extended near field are presented addressing typical length and time scales and especially turbulence quantities. Progressing from the near field to the far field wake instability mechanisms are explained along with their relevance for wake vortex decay. Characteristic quantities are given for the short and long wave instabilities associated vortex merging and wakes consisting of two and four trailing vortices. A non-dimensional frequency parameter is introduced to classify the main instability types. Means for wake vortex alleviations are described aimed at influencing the wake vortex turbulence field or triggering and amplifying the inherent instabilities. The methods discussed include passive means such as the effects of spoilers, differential flap setting and four-vortex systems and active means using oscillating flaps or auxiliary devices.

Breitsamter, C. and Allen, A.

"TRANSPORT AIRCRAFT WAKE INFLUENCED BY OSCILLATING WINGLET FLAPS"

J. Aircraft, Vol. 46, No. 1, Jan.-Feb. 2009, pp. 175-188

The wake vortex development in the near field and extended near field behind a four-engine large transport aircraft model fitted with an active winglet is presented. A detailed wind-tunnel investigation is conducted using a half-model focusing on the high-lift case of a typical approach configuration at a Reynolds number of 500000 based on the wing mean aerodynamic chord and an angle of attack of 6.5 deg. The flow field is observed using advanced hot-wire anemometry mainly focusing on the crossflow plane at 5.6 spans downstream of the model. Based on the time-dependent velocity components the wake flow field is analyzed by distributions of mean vorticity, turbulence intensities, and spectral densities. Seven main vortical structures dominating the near-field wing vortex sheet roll up and merge to form the remaining trailing vortex in the extended near field. Using oscillating winglet flaps, the velocity fluctuations at the core region of the remaining vortex are significantly influenced. Distinct narrowband concentrations of the turbulent kinetic energy can be found for the farthest downstream plane documenting the presence of the disturbances generated by the winglet flaps which result in an amplification of inherent far-field instabilities.

Breitsamter, C. and Jung, U.

"VORTEX INTERACTIONS WITH WAKES: WING ELEMENTS, FUSELAGE, AND LANDING GEAR"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 200.

The presentation concentrates on the influence of wing elements, the fuselage and the landing gear on the wake vortex formation and evolution in the near field and extended near field of a typical four engine wide body transport aircraft configuration. To evaluate the influence of the main components, the fuselage alone and the configurations without and with horizontal tail plane, nacelles, winglet, and landing gear are investigated in comparison to a baseline configuration. The wind tunnel model used consists of a detailed half model studied in a typical high lift approach configuration. The flow fields are analyzed by velocity, vorticity, and turbulence intensity fields as well as by spectral densities. The associated time dependent velocities are measured based on advanced hot-wire anemometry using miniature triple-wire probes. The cross flow is inspected at several planes covering a downstream distance up to 5 spans. The wing elements studied affect the near field wake vortex formation with respect to position and strength of the main near field vortices during the roll-up process. The overall influence on the remaining rolled-up vortex is small, nevertheless some changes in velocity gradients and turbulence intensities can be observed. The fuselage alone case exhibits the presence of three vortices, namely a vortex linked to separation at the inclined fuselage, a vortex emanating from the belly fairing and a vortex shed at the tail cone. The sense of rotation of the latter is opposite to that of the other two vortices. The wake of the fuselage, particularly due to the thick turbulent boundary layer, creates a concentrated turbulent region stretched in vertical direction because of fuselage inclination and wing downwash. This turbulent region affects strongly the inboard wake vortices, especially the wing-fuselage vortex and the horizontal tail plane vortex. Thus, the latter becomes significantly weakened within the extended near field region.

Breitsamter, C. and Laschka, B.

"VORTICAL FLOWFIELD STRUCTURE AT FORWARD SWEEP-WING CONFIGURATIONS"

Journal of Aircraft, Vol. 38, No. 2, March-April 2001, pp. 193-207,

Extensive aerodynamic investigations have been carried out on forward swept-wing configurations with a wing sweep of -40 degrees. A generic wing-body model with removable aft swept canards is used to measure the instantaneous velocities in several crossflow planes applying advanced hot-wire anemometry. The tests were made at 10-, 20-, and 30-degree angle of attack at a Reynolds number of 460000. Detailed surveys of mean and rms velocities show that at moderate angles of attack strong wing leading-edge vortices are generated rotating opposite in a sense to the wing tip vortices. At higher incidences trailing-edge vortices are shed at the inner-wing part with the same sense of rotation as the wing tip vortices. The canard vortices pass the wing leading-edge relatively high, and after the onset of wing vortices they are moved upward and outboard. The interference between these vortices is studied in detail by analyzing the associated turbulent flow structure. Vortex bursting over the wing occurs already at moderate angles of attack. Downstream, the highest turbulence intensities are found in an annular region around the burst vortex core, where fluctuations are significantly channeled into a narrow band.

Breitsamter, C., Bellastrada, C. and Laschka, B.

"INVESTIGATIONS ON THE TURBULENT WAKE VORTEX FLOW OF LARGE TRANSPORT AIRCRAFT"

ICAS-2002-3.8.2, Toronto, Canada, September 2002

The wake vortex formation and development behind a four-engine large transport aircraft model is studied in detail. Wind tunnel experiments have been conducted on an 1:22.5 scaled half-model in landing configuration at angle of attack of 9.5 degrees. The wake flowfield is carefully surveyed at six cross-flow planes located over a distance of 6 wing spans using advanced hot-wire anemometry. The results obtained include velocity, vorticity and Reynolds stress fields and spectral densities. Specific wake vortex instability mechanisms were analyzed while vortex meandering acts as a broad-band turbulence phenomenon.

Brend, M. A. and Thomas, P. J.

"DECAY OF VORTEX RINGS IN A ROTATING FLUID"

Physics of Fluids, Vol. 21, 2009, pp. 044105-1 - 044105-5..

Vortex rings propagating through a rotating fluid, along the axis of rotation, are studied experimentally. The length, x , traveled by the rings until they have completely decayed is measured. In agreement with theoretical arguments based on the Taylor-Proudman theorem it is observed that the value of x decreases with decreasing Rossby number, Ro . For the parameter range investigated here we determine an overall, global trend for the scaling of the mean decay length that can be roughly summarized by the expression $(x/D) = 4.77$ times Ro to the 1.06 power, where D is the diameter of the generator nozzle used to produce the vortex rings.

Brendmoen, J. V. and Netzer, D. W.

"ATMOSPHERIC DISPERSION OF HIGH VELOCITY JETS"

NPS-67-79-012, November 1979, Naval Postgraduate School, Monterey, CA.

A neutrally stable atmospheric surface layer was simulated in a low-speed wind tunnel by tripping the boundary layer with a fence and letting the turbulent flow develop over a length of roughness elements. Turbojet exhaust dispersion characteristics, simulated by a burner/nozzle system, were investigated by measuring the horizontal and vertical temperature profiles at axial stations downwind from the nozzle exit. Dispersion sensitivity to different nozzle exit conditions, angles of incidence to the wind, and nozzle surface blockage were investigated. The results were compared to dispersion methods used in the Air Quality Assessment Model (AQAM). It was found that (1) the experimental jet penetration length was much shorter than that assumed in AQAM, (2) the horizontal jet exhibited plume rise, (3) the initial dispersion coefficients were a function of wind direction, and (4) the plume spreading rate was more rapid than for low velocity, elevated sources in neutrally stable atmospheric conditions.

Brennenstuhl, U. and Hummel, D.

"VORTEX FORMATION OVER DOUBLE-DELTA WINGS"

ICAS 1982, August 1982, Seattle, WA.

Low-speed wind-tunnel tests have been carried out on a series of double-delta wings. The effects of variations in leading-edge kink angle and in kink position have been investigated by means of three-component, pressure distribution and flow field measurements as well as by flow visualization at $Re = 1,300,000$. At small angles of attack two primary vortices exist on each side of the wing, originating from the apex and from the leading-edge kink. At moderate kink angles these two vortices join each other with increasing angle of attack. The junction process is analyzed in detail and is interpreted as a 'potential flow effect.' At very large angles of attack vortex breakdown occurs within the joined vortices, which leads to the limitations of the aerodynamic coefficients.

Brenner, F.

"AIR TRAFFIC CONTROL PROCEDURES FOR THE AVOIDANCE OF WAKE VORTEX ENCOUNTERS"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 4-1 to 4-14

DFS Deutsche Flugsicherung GmbH is the corporatized provider of air traffic control services in Germany. The German wake turbulence separation minima are following those prescribed by ICAO, yet it is possible to deviate from these values. How a vortex detection and warning system could be used to improve the situation is discussed.

Brewer, B. S. and Brewer, J. S.

"WAKE TURBULENCE AVOIDANCE LIGHTS"

US Patent 5,949,353, September 1999.

A wake turbulence light system is provided including an aircraft runway with a periphery including a pair of long parallel side edges and a pair of short end edges. Also included is a plurality of light assemblies mounted along at least one of the side edges of the runway in spaced relationship. A plurality of sensors is adapted for indicating a point on the runway at which a plane has departed. Finally, control circuitry is connected between the light assemblies and the sensors for indicating a location of the point by illuminating a light assembly adjacent thereto, as detected by the sensor.

Briassulis, G. and Andreopoulos, J.

"WAKE STRUCTURE OF A HELICOPTER ROTOR IN FORWARD FLIGHT"

The wake of an idealized two-bladed helicopter rotor in forward flight has been experimentally investigated using hot-wire anemometry techniques. A model was designed, constructed, installed, and tested in a wind tunnel. Time-dependent measurements of three-dimensional velocity vectors were obtained for two pitch angles corresponding to a Reynolds number based on the rotor tip rotational velocity and blade chord of 82,000 and 62,000, respectively, at an advance ratio of 0.15. The results include time- and phase-averaged data of mean velocity components and turbulence intensities, as well as spectral analysis. Profiles of the streamwise component of the velocity vector have shown the existence of a z component of the vorticity vector. Analysis of the vertical and the transverse component of the velocity vector also revealed the existence of a z component of the vorticity vector at both edges of the wake. Large levels of turbulent kinetic energy were found almost everywhere in the wake. Turbulence intensity due to the presence of the counterclockwise rotating vortex reached the maximum values of 22.4 and 19% for pitch angle 10 and 6 deg, respectively. Spectral analysis of the velocity components revealed peaks of power spectral densities at frequencies two or four times higher than the blade passage frequency. This suggests a possible breakup of the vortex sheets roll-up or tip vortices due to large scale instabilities.

Bricteux, L.

"SIMULATION OF TURBULENT AIRCRAFT WAKE VORTEX FLOWS AND THEIR IMPACT ON THE SIGNALS RETURNED BY A COHERENT DOPPLER LIDAR SYSTEM"

PhD Thesis, March 2008, University Catholique de Louvain, Louvain-la-Neuve, Belgium.

This thesis concerns the numerical simulation and the remote sensing of aircraft wake vortex flows. Due to its lift force, an aircraft releases large scale swirling flows (vortices) in its wake. As these vortices can impact significantly the trajectory of a following aircraft, their study is of great importance for practical applications concerning safety of air traffic management. The investigation carried here is twofold: it concerns, on one hand, the physics and the numerical simulation of aircraft wake vortices and, on the other hand, the technique to detect those vortices and measure their properties. The numerical simulation of aircraft wake vortices requires high order and energy conserving codes. Moreover, as aircraft wake vortex flows are turbulent, subgrid scale (SGS) models are required to perform Large Eddy Simulation (LES) of these flows. In the first part of this work, the numerical codes used (here spectral and high order finite differences) are presented and validated. Several SGS models are presented and their ability to perform LES of vortical flows, also in presence of a ground is assessed. In particular a new 'multiscale' model with a natural wall damping behavior has been developed and investigated: its performance is very good. In the second part, two flows relevant to the wake vortex problem are analyzed. The LES of a wake vortex system in a weakly turbulent atmosphere allowed highlighting the turbulent equilibrium state of such a flow. LES of wake vortices in ground effect, with and without wind, were also carried out. These simulations help to better understand the physics of wake vortices. In the last part, we simulate the remote sensing of aircraft wake vortices using a ground-based LIDAR (Light Detection And Ranging) system. The aim of this LIDAR is to sense aircraft wake vortices and turbulent winds. As the LIDAR signals are simulated using realistic parameters and realistic turbulent flows, this work serves as support in the design of an airport-based LIDAR system.

Bricteux, L., Duponcheel, M. and Winckelmans, G.

"A NEW MULTISCALE MODEL WITH PROPER BEHAVIOR IN BOTH VORTEX FLOWS AND WALL BOUNDED FLOWS"

In Direct and Large-Eddy Simulation, Vol. VII, Series 13, 2010, pp. 253-258.

A new subgrid-scale (SGS) model which has an adequate behavior in both vortical flows and wall-bounded flows is proposed. In wall-bounded flows computed using wall-resolved LES, the theory predicts that the SGS dissipation should vanish with a y to the +3-power behavior near the wall. In the case of vortex flows, one needs to have models which do not dissipate energy in the strongly vortical and essentially laminar part of the flow, e.g. in vortex core regions. The model presented here aims at combining the strengths of two models as it is a regularized variational multiscale model, thus acting on the high pass filtered LES field, and for which the sub-grid scale viscosity is evaluated using the wall adapting local eddy viscosity scaling of Nicoud and Ducros, itself computed using the high pass filtered LES field. Thus, this model is only active when there is a significant high wavenumber content in the flow and it has a natural near wall damping behavior. The ability of this model to simulate vortex and wall-bounded flows is demonstrated on three test cases. The first case is the turbulent channel flow. The second case concerns a four-vortex system. The third case concerns a two-vortex system in ground effect. It is shown that this new model allows to perform successfully LES of these flows with the proper dissipative behavior in both near wall and vortical regions. The LES are performed using a parallel fourth order code based on finite differences.

Bridges, D. H.

"FINITE WING LIFT-CURVE SLOPE CALCULATIONS USING LIFTING-LINE THEORY"

AIAA Paper 2005-4839, June 2005, Toronto, Canada.

Lifting-line theory is a valuable tool for preliminary evaluation of wing planform designs. It has been used to predict the induced drag of finite wings, and such results for untwisted wings have been tabulated in basic aerodynamics textbooks for use by students and others in evaluating finite wing designs. It is also possible to compute the lift-curve slope of a finite wing using the theory, and yet few such tabulated results exist for the effects of taper ratio and aspect ratio on lift-curve slopes of finite wings. This paper describes such calculations and contains the figures necessary to predict the effects of aspect ratio and taper ratio on the lift-curve slopes of linearly-tapered finite wings.

Bridges, D. H.

"ESTIMATE OF THE DISTURBANCE ENERGY IN AN ASYMMETRIC VORTEX WAKE"

AIAA Paper 2008-4180, June 2008, Seattle, WA.

Previous studies have suggested that the asymmetric vortex wake which developed behind an axisymmetric body at high angle of attack is the result of the amplification of a disturbance introduced at the tip of the body, implying that the asymmetric vortex wake problem is a stability problem. Measurements by previous researchers have shown the exponential growth of the so-called 'distortion energy' in the wake, supporting the stability problem hypothesis. The definition of distortion energy, more generally described as a disturbance energy, chosen by these investigators requires a large set of measurements for a single result, and so another less experimentally-expensive definition of disturbance energy is desired. This study uses the potential flow solution for two vortices behind a circular cylinder in cross flow as a 'virtual wind tunnel' to explore the validity of a particular definition of the disturbance energy. This definition, the product of the local section side force coefficient, the vortex separation distance, and the angle between the line connecting the vortices and the perpendicular to the incidence plane, is shown to exhibit the desired variations and is thus a plausible measure of the disturbance energy in the vortex wake.

Bright, D. R., Lack, S. A. and Sparks, J. A.

"A SUMMARY OF TURBULENCE FORECASTING TECHNIQUES USED BY THE NATIONAL WEATHER SERVICE"

In *Aviation Turbulence*, edited by R. Sharman and T. Lane, Chapter 10, 2016, Springer International Publishing Switzerland, pp. 213-226.

A summary of turbulence forecasting by the US National Weather Service (NWS) is provided. This chapter begins with a historical perspective, beginning with the Wright brothers and ending with NextGen. Following the historical perspective, present-day aviation-based meteorological operations are described. This discussion covers the services provided by the NWS and its partners and includes a foundational summary of present-day (2015) forecasting techniques. This chapter closes with a narrative on current and future prediction, built around numerical models and ensemble systems. These systems will drive intelligent information extraction and decision support services provided by operational meteorologists, leading to a safer and weather-ready airspace.

Brillant, G., Chilla, F. and Pinton, J.-F.

"TRANSMISSION OF SOUND THROUGH A SINGLE VORTEX"

Eur. Physics J. Vol. B37, 2004, pp. 229-239

We investigate experimentally the deformation of acoustic wavefronts after crossing of a single, isolated vortex in free space. The incident sound wavelength can be varied in a large domain. We study the wavefronts at variable distance after transmission through the vortex, when the wavelength and the vortex strength are varied. For small wavelength our results are in very good agreement with predictions and simulations based on geometrical acoustics principles. However, as the sound wavelength increases to value comparable with the vortex diameter, the deformation of the wavefronts

shows the development of scattering contributions, with characteristics in agreement with recent theoretical and numerical studies.

Brion, V. and Jacquin, L.

"MEASUREMENTS OF A TURBULENT VORTEX PAIR USING TIME RESOLVED PIV"

AIAA Paper No. 2011-3892, June 2011, Honolulu, Hawaii.

Stereoscopic time resolved PIV is applied to study vortex pair instabilities. The two vortices are generated by a split wing apparatus that is designed to fasten the development of cooperative instabilities such as the Crow and Widnall modes thanks to a short vortex separation and a strong circulation. We use spectral analysis and vortex center detection to validate the presence of both instabilities. In addition, we characterize these instabilities in terms of wavelength, growth rate and of the direction of the oscillations of the vortices. Our results are found to be in good agreement with theoretical results taken from literature. The structure of the flow is found to be richer than the sole instabilities, with the presence of strong turbulence levels at the outskirts of the vortices, that results from the elongation of vorticity at the leading stagnation point of the vortex pair and wrapping of this vorticity around the vortex cores.

Brion, V. and Jacquin, L.

"ANALYSIS OF THE TIP LEAKAGE VORTEX DYNAMICS WITH A SLOTTED WING APPARATUS"

9th European Turbomachinery Conference, March 2011, Istanbul, Turkey.

In this paper we analyze the validity of replacing the casing wall in the tip leakage vortex flow by an image vortex. The study is based on an experimental set-up that allows two academic flow configurations. The first configuration is an idealized tip leakage vortex configuration with one wing set perpendicular to a flat plate playing the role of the casing wall. In the second configuration, the flat plate is replaced by an image wing to create the image vortex. The wing is rectangular and placed at 8 degrees angle of attack in a uniform flow. The distance between the flat plate and the wing tip can be adjusted between 1 and 10 percent of wing chord. The objective of the study is to examine the validity of the image vortex approach through the comparison of the vortex characteristics and evolution in the two flow configurations when the gap size is varied. The mean flow exhibits important differences, most notably concerning the vortex trajectory, size and circulation. The unsteady flow is analyzed with the objective of verifying the presence of the Crow instability in the tip leakage vortex, as indicated in the work of Bae. The Crow instability is however only observed in the image vortex flow. Comments on this result are given in the conclusion.

Brion, V., Sipp, D. and Jacquin, L.

"OSCILLATIONS OF A VORTEX PAIR"

11th ONERA-DLR Aerospace Symposium, February 2011, Toulouse, France.

Aircraft trailing vortices may, under specific meteorological conditions, evolve into cirrus clouds and significantly impact the climate of a region where air traffic is dense. To understand the formation of these clouds, several authors have shown the importance of the secondary wake forming above the primary wake. An accepted mechanism for the generation of this secondary wake is the baroclinic production of vorticity at the separatrix between the atmosphere and the contrail. Here we present another mechanism that could add up to the latter. We describe it thanks to a viscous linear stability analysis of a realistic counter-rotating vortex pair modelling the trailing vortices. A family of unstable modes is found whose most unstable mode is two-dimensional and leads to the formation of a secondary wake in agreement with observations. The instability induces growing oscillations of the vortex pair when it descends with a Strouhal number equal to 0.2.

Brion, V., Sipp, D. and Jacquin, L.

"INFLUENCE OF AXIAL FLOW AND ASPECT RATIO ON THE STABILITY OF VORTEX PAIRS"

Bulletin American Physical Society, Vol. 51, No. 9, 2006, p. 91.

A planar vortex pair with axial flow is simulated using DNS. The evolution of the flow is stopped when the aspect ratio of the dipole has reached a desired value. Values between 0.2 and 0.4 are investigated. A tail of vorticity forms downstream the dipole as it evolves toward higher aspect ratios. Using three-dimensional stability analyses, we study the sensibility of the Widnall modes of the dipole about the swirl number of the base flow and the aspect ratio. Those short-wave modes are recovered for two-dimensional vortex pairs. New modes appear as we progressively increase the axial flow. The increase in aspect ratio seems to widen the bands of instability. Long time instability modes are then compared to short time modes that are found by a code of optimal perturbation based on an adjoint method. We show that the perturbation that gives the highest increase in energy at short time is localized in the vicinity the center of each vortex whereas the perturbation that gives the highest increase in energy at long time is localized at the periphery of the vortices.

Brion, V., Sipp, D. and Jacquin, L.

"OPTIMAL AMPLIFICATION OF THE CROW INSTABILITY"

Physics of Fluids, Vol. 19, 2007, pp. 111703-1 to 111703-4

A mechanism for promoting the Crow instability in a counter-rotating vortex pair is presented within the framework of linear dynamics. It consists of (i) the creation of a periodic array of vortex rings along the length of the vortices by stretching of vorticity at the leading hyperbolic point of the dipole, and (ii)

the deformation of the vortices by the vortex rings leading to the Crow instability. A reduction of the characteristic time of the Crow instability by a factor of roughly 2 can be obtained by this mechanism.

Bristol, R.

"AN EXPERIMENTAL INVESTIGATION INTO THE WAKE VORTEX ROLL-UP OF A RECTANGULAR AIRFOIL"

MS Thesis, 1999, University of California, Berkeley, CA.

The roll-up process of trailing vortices from small rectangular airfoils was studied in a towing tank using a particle imaging velocimetry technique. The measurements were made in a Eulerian frame, that is, the measurement plane remained fixed while the wing swept by. Chord-based Reynolds numbers ranged from 13000 to 67000 and circulation-based Reynolds numbers from 2300 to 17000. The flow was interrogated at distances from 0.2 chord to 60 chords aft of the wing. Data were analyzed for both velocity and velocity-gradient fields perpendicular to the path of travel of the wing. Much of the roll-up process occurred on the airfoil itself; the vortices were completely rolled-up within one span. Unsteady strands of oppositely-signed vorticity were observed in the rolling-up vortex sheet immediately aft of the wing. Fluctuating structures such as these have rarely been seen before, as most studies have employed point measurements, therefore obtaining a time-averaged picture of the overall flow field. Using a PIV technique, this study made essentially instantaneous measurements in a plane, and thus was able to capture unsteady effects. The Lamb-Oseen distribution was found to be a fair fit to the vortices, although the reader is cautioned the actual vortices were not quite azimuthally symmetric.

Bristol, R. L., Ortega, J. M. and Savas, O.

"EXPERIMENTAL STUDY OF COROTATING WAKE-VORTEX MERGER AT REYNOLDS NUMBERS OF ORDER 100,000"

AIAA Journal, Vol. 41, No. 4, April 2003, pp. 741-744.

Corotating tip-flap vortex pairs are studied at Re of order 100,000. The evolution of the velocity field at a fixed cross section is recorded, yielding measures of the circulation ratio, separation, and vortex size. The pair is observed to merge within about one orbital period. Flow visualization clearly shows the three-dimensional nature of this process, with the appearance of strong sinuous disturbances on the weaker flap vortices, and to a lesser extent on the tip vortex. The wave number of this disturbance and its alignment with the extensional axis of the straining field from the partner vortex suggest it to be an example of an elliptical instability. For such an instability driven by the straining field of the partner vortex, the growth rate scales as the inverse of the square of the vortex separation, $1/(d^2)$. This growth rate matches the scaling of the orbit period, thus, yielding finite amplitudes within one orbit. This provides an explanation for the observed merger in about one orbit, even for vortices spaced too far apart to merge in two dimensions.

Bristol, R., Ortega, J. and Savas, O.

"A TOWING TANK STUDY OF AIRFOIL WAKE VORTICES AT CIRCULATION-BASED REYNOLDS NUMBER OF 10,000"

AIAA Paper No. 1999-3419, Norfolk, VA, June-July 1999.

An experimental study of airfoil wake vortices was carried out in a 70 m long towing tank. Circulation based Reynolds numbers ranged from 80,000 to 300,000. PIV images were recorded up to 120 spans downstream of the airfoil and processed with an adaptive Lagrangian Parcel Tracking algorithm, allowing velocity and velocity-gradient fields to be obtained. Airfoils with and without one symmetrical flap were used, generating either two or one pair of counter-rotating vortices, respectively. The structure of individual vortices is well described by a Gaussian vorticity distribution. The wakes from flapped airfoils show merger of the co-rotating vortices. For this study, merger was based on the time for the merged vortex to axisymmetrize itself and descend in a straight path, as marked by buoyant particles. The merger consistently reaches completion in one to two orbit periods over a wide range of Reynolds numbers and initial vortex separations. Fluctuating moments of vorticity indicate that the merger process is inherently three-dimensional. Isolated vortices do not exhibit measurable decay. The present study extends the maximum circulation-based Reynolds number over that of a recent paper by Chen, Jacob, and Savas by a factor of 5, yet the qualitative features of the flow remain the same.

Britt, C. L.

"ESTIMATION OF VORTEX CHARACTERISTICS FROM COHERENT LIDAR MEASUREMENTS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 280-291

This presentation outlines a technique for the estimation of aircraft wake vortex position and strength from Doppler measurements by a pulsed coherent lidar. A minimum variance method is used to estimate the vortex circulation from maximum velocities detected by the lidar at various range bins along the line of sight during a lidar scan. The circulation is calculated at each point in the scan, and the points of maximum circulation provide the positions of both positive and negative vortices in the scan volume. The methods are currently being used in the NASA/LaRC wake vortex lidar and are providing excellent results, with over 700 aircraft vortices successfully detected and tracked during field experiments.

Britt, C. L.

"ESTIMATION OF AIRCRAFT WAKE VORTEX SIZE AND STRENGTH FROM COHERENT PULSED LIDAR MEASUREMENTS"

9th Conference on Coherent Laser Radar, Paper Tu18, Linkoping, Sweden, June 1997

A mathematical framework has been developed to estimate wake vortex characteristics from lidar measurement data. The estimations are optimal in the sense that they minimize the variance of the errors between the measurement data and a model of the lidar measurement process. Calculations with simulated measurement data indicate that the estimation equations are valid and that the techniques work as expected.

Britt, C. L., Kelly, C. W. and Nguyen, D. P.

"ALGORITHMS FOR GENERATION OF WIND TURBULENCE PROFILES FROM PULSED LIDAR MEASUREMENTS"

RTI/8348/010-01F, RTI International, Hampton, VA, March 2003

Methodology and algorithms are suggested for a pulsed lidar system that will provide EDR and TKE altitude profiles in real time for future experimental or operational vortex detection programs. Archived raw lidar data have been used to develop and test the algorithms and to develop a practical set of algorithm parameters. Numerous cases from past AVOSS tests have been analyzed and results comparing the lidar estimates with tower measurements obtained during the 2000 DFW AVOSS experiments are presented.

Britt, C. L., Nguyen, D. P. C. and Koch, G.

"PULSED LIDAR MEASUREMENTS OF AIRCRAFT WAKE VORTICES AT DFW AND JFK"

AIAA Paper No. 1999-0982, Reno, NV, January 1999

During 1997, extensive measurements of wake vortices from landing aircraft were conducted using a state-of-the art pulsed coherent lidar system constructed at the National Aeronautics and Space Administration's Langley Research Center. The measurements were part of the NASA Aircraft Vortex Spacing System (AVOSS) program to quantify and predict the behavior of vortices generated by aircraft during landing approach and takeoff. Predicting reliable real-time vortex hazards and behavior may permit ATC spacing rules to be adjusted to more closely reflect the true vortex hazards, and could lead to higher airport capacity in the future. This paper presents examples of the results of vortex measurements under various conditions, along with a brief description of the NASA lidar system, the AVOSS concept, and the field deployments to John F. Kennedy and Dallas Fort-Worth International Airports.

Britton, J. W.

"SOME REMARKS ON EN-ROUTE VORTEX ENCOUNTERS"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 243-246

Encounters with vortex wakes can and have occurred during cruising flight on airways. Observations at RAE Bedford indicate that trailing vortices may persist for more than two minutes after the passage of an intercontinental airliner in cruising flight at high altitude.

Britton, J. W.

"SOME OBSERVATIONS OF THE BEHAVIOR OF THE VORTEX WAKE OF A VC 10 AIRCRAFT"

TM FS-105, February 1977, Royal Aircraft Establishment, Farnborough, England.

Some observations of the nature and persistence of the trailing vortices of a VC 10 aircraft are presented. Particular attention is drawn to the difference between the wakes for the aircraft in the cruise and approach/landing configurations. The effects of thermals and of the wakes of airfield buildings on the position and persistence of the wake are also described.

Brocklehurst, A. and Barakos, G. N.

"A REVIEW OF HELICOPTER ROTOR BLADE TIP SHAPES"

Progress in Aerospace Sciences, Vol. 56, 2013, pp. 35-74.

A review of helicopter rotor blade tip design technology has been carried out with a view to understanding subsequent computations to evaluate the performance of new tip designs. The review starts by briefly looking at (fixed) wing tip design concepts and the underlying fluid mechanics on which they are based to see if there is any carry-over of ideas on which improved tip design concepts might be based. Then, rotor blade tip shapes that have been used, or suggested for use, on past and present rotorcraft are examined to obtain a better understanding of the helicopter tip design problem. In parallel, the review traces the development of analysis tools to evaluate the performance of the rotor and blade tip design. In the past, the designer relied heavily on classical aerodynamic knowledge, supplemented by experience and intuition, supported by wind tunnel and model rotor testing, and relatively low-order aerodynamic calculations. New rotor designs were, and still are the subject of intensive flight test verification. However, recent development of Computational Fluid Dynamics now offers an opportunity to accurately predict the viscous, compressible flow-field in the tip region, and thus predict the performance of new rotor and tip designs, provided that the solver has adequate resolution, is able to handle all aspects of the helicopter problem, and sufficient computational resources are available to complete the design in a practical time-scale.

Brockman, P.

"WAKE VORTEX LIDAR SYSTEM: OVERVIEW OF LARC PULSED LIDAR MEASUREMENTS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 247-260

The NASA Langley Research Center trailer-mounted Pulsed Lidar Facility is described including: lasers, transceivers, scanner, and data systems. Results from deployments at Langley Air Force Base and Norfolk Airport are given and future deployments to JFK and DFW airports are described. Results include data from two micrometer lasers, one a 20 pulse per second, 3 mi, 100 ns system developed by Lockheed Sanders for the Air Force and modified by NASA and a 100 pulse per second, 7 mi, 380 ns system developed by Coherent Technologies Inc. under a NASA SBIR. A 1.5 micrometer, 10 mi, 100 ns laser being developed by Lite Cycles Inc. is described. Results from two data systems, one developed by CTI under a NASA SBIR and the second by Research Triangle Institute and NASA are described.

Brockman, P., Barker, Jr., B. C., Koch, G. J., Nguyen, D. P. C., Britt, Jr., C. L. and Petros, M.

"COHERENT PULSED LIDAR SENSING OF WAKE VORTEX POSITION AND STRENGTH, WINDS AND TURBULENCE IN THE TERMINAL AREA"

Tenth Biennial Coherent Laser Radar Technology and Applications Conference, Mount Hood, OR, November 1999.

NASA Langley Research Center has field tested a 2.0 gm, 100 Hertz, pulsed coherent lidar to detect and characterize wake vortices and to measure atmospheric winds and turbulence. The quantification of aircraft wake-vortex hazards is being addressed by the Wake Vortex Lidar Project as part of Aircraft Vortex Spacing System (AVOSS), which is under the Reduced Spacing Operations Element of the Terminal Area Productivity Program. These hazards currently set the minimum, fixed separation distance between two aircraft and affect the number of takeoff and landing operations on a single runway under Instrument Meteorological Conditions. The AVOSS concept seeks to safely reduce aircraft separation distances, when weather conditions permit, to increase the operational capacity of major airports. The current NASA wake-vortex research efforts focus on developing and validating wake vortex encounter models, wake decay and advection models, and wake sensing technologies. These technologies will be incorporated into an automated AVOSS that can properly select safe separation distances for different weather conditions, based on the aircraft pair and predicted/measured vortex behavior. The sensor subsystem efforts focus on developing and validating wake sensing technologies. The lidar system has been field-tested to provide real-time wake vortex trajectory and strength data to AVOSS for wake prediction verification. Wake vortices, atmospheric winds, and turbulence products have been generated from processing the lidar data collected during deployments to Norfolk, John F. Kennedy, and Dallas/Fort Worth International Airports.

Brodecki, M., Subbarao, K. and Chu, Q.-P.

"FORMATION FLIGHT CONTROL SYSTEM FOR IN-FLIGHT SWEET SPOT ESTIMATION"

AIAA Paper 2013-1037, January 2013, Grapevine, TX.

A formation flight control system has been designed that addresses the unique environment encountered by aircraft flying in formation and in the upwash of the leading aircraft. To test the control system a simulation environment has been created that adequately represents the aerodynamic

coupling effects between aircraft flying in formation and implements an INDI-based formation control system. Since the exact position of the sweet spot cannot be known the research presented in this paper used an advanced extremum seeking algorithm that utilizes an EKF to estimate the gradients. Simulations have shown the algorithm to be robust to errors induced by turbulence and having the ability to consistently find the sweet spot.

Broderick, A. J., Bevilaqua, P., Crouch, J., Gregory, F., Hussain, F., Jeffers, B. F., Newton, D. W., Nguyen, D. P., Powell, J. D., Spain, A. T., Stone, R. P. and Willcox, K.

"WAKE TURBULENCE -- AN OBSTACLE TO INCREASED AIR TRAFFIC CAPACITY"

National Research Council, The National Academies Press, Washington, DC, 2008.

The report is an independent assessment of the nation's wake turbulence research and development program to overcome wake turbulence challenges. The report identified the most important challenges to address and why; an assessment of the current relevant research being conducted by NASA, the FAA and other federal government agencies; and a review of research being conducted by nonfederal government organizations within the US and by foreign organizations in wake turbulence. The report presents a recommended priority and level of effort for the wake turbulence challenges.

Brons, M., Shen, W. Z., Sorensen, J. N. and Zhu, W. J.

"THE INFLUENCE OF IMPERFECTIONS ON THE FLOW STRUCTURE OF STEADY VORTEX BREAKDOWN BUBBLES"

Journal of Fluid Mechanics, Vol. 578, 2007, pp. 453-466.

Vortex breakdown bubbles in the flow in a closed cylinder with a rotating end-cover have previously been successfully simulated by axisymmetric codes in the steady range. However, high-resolution experiments indicate a complicated open bubble structure incompatible with axisymmetry. Numerical studies with generic imperfections in the flow have revealed that the axisymmetric bubble is highly sensitive to imperfections, and that this may resolve the apparent paradox. However, little is known about the influence of specific, physical perturbations on the flow structure. We perform fully three-dimensional simulations of the flow with two independent perturbations: an inclination of the fixed cover and a displacement of the rotating cover. We show that perturbations below a realistic experimental uncertainty may give rise to flow structures resembling those obtained in experiments, that the two perturbations may interact and annihilate their effects, and that the fractal dimension associated with the emptying of the bubble can quantitatively be linked to the visual bubble structure.

Brons, M., Thompson, M. C. and Hourigan, K.

"DYE VISUALIZATION NEAR A THREE-DIMENSIONAL STAGNATION POINT: APPLICATION TO THE VORTEX BREAKDOWN BUBBLE"

Journal of Fluid Mechanics, Vol. 622, 2009, pp. 177-194.

An analytical model, based on the Fokker-Planck equation, is constructed of the dye visualization expected near a three-dimensional stagnation point in a swirling fluid flow. The model is found to predict dye traces that oscillate in density and position in the meridional plane in which swirling flows are typically visualized. Predictions based on the model are made for the steady vortex breakdown bubble in a torsionally driven cylinder and compared with computational fluid dynamics predictions and experimental observations. Previous experimental observations using tracer visualization techniques have suggested that even for low-Reynolds-number flows, the steady vortex breakdown bubble in a torsionally driven cylinder is not axisymmetric and has an inflow/outflow asymmetry at its tail. Recent numerical and theoretical studies show that the asymmetry of the vortex breakdown bubble, and consequently its open nature, can be explained by the very small imperfections that are present in any experimental rig. Distinct from this, here it is shown that even for a perfectly axisymmetric flow and breakdown bubble, the combined effect of dye diffusion and the inevitable small errors in the dye injection position led to the false perception of an open bubble structure with folds near the lower stagnation point. Furthermore, the asymmetries in the predicted flow structures can be remarkably like those observed in flow observations and computational predictions with geometric asymmetries of the rig. Thus, when interpreting dye-visualization patterns in steady flow, even if axisymmetric flow can be achieved, it is important to consider the relative diffusivity of the dye and the accuracy of its injection..

Brookfield, J. M., Waitz, I. A. and Sell, J.

"WAKE DECAY: EFFECT OF FREESTREAM SWIRL"

International Gas Turbine and Aeroengine Congress and Exhibition, June 1997, Orlando, FL.

A study of the effects of freestream swirl on the decay characteristics of wakes shed from a rotating blade row is presented. The freestream swirl behind the rotor causes the wakes to skew tangentially, stretching the wakes as they are convected from the rotor to the stator. The effect of stretching on wake decay is illustrated using a simplified two-dimensional model. The model is described and the results are compared to 1) measurements from a two-dimensional cascade facility where no stretching or skewing of the wake occurs, 2) solutions obtained using a three-dimensional, Reynolds-averaged Navier-Stokes solver, and 3) experimental wake measurements taken behind a low hub-to-tip ratio fan. For typical fan geometries with hub-to-tip ratios of approximately 0.5 and rotor-stator spacings of one to two rotor chord lengths, the wake can be stretched by over 50 percent. The stretching increases the mixing rate which leads to a reduction in the mean wake velocity deficit of approximately 30 percent and a widening of the wake of about 15 percent. These effects account for much of the difference seen between cascade wake measurements and those taken behind rotating fan blade rows.

Brooks, T. F. and Marcolini, M. A.

"AIRFOIL TIP VORTEX FORMATION NOISE"

AIAA Journal, Vol. 24, No. 2, February 1986, pp. 246-252

Special data are presented for the noise produced due to turbulent three-dimensional vortex flow existing near the rounded tip of lifting airfoils. The results are obtained by the comparison of sets of two- and three-dimensional test data for different airfoil model sizes, angles of attack, and tunnel flow velocities. Microphone cross-correlation and cross-spectral methods are used to determine the radiated noise. Corrections are made for tunnel shear-layer and source directivity effects. Interpretation of the results is aided by a three-dimensional flow analysis developed for this study which determines open wind tunnel and finite aspect ratio corrections heretofore neglected in tip vortex studies. Hot-wire measurements are made in the tip vortex formation region for the specification of governing flow parameters. The spectral data are normalized in a format considered most useful for quantitative prediction of this noise mechanism for practical systems such as helicopter rotors. A recommended prediction method is given.

Brossard, C., Monnier, J.-C., Barricau, P., Vandernoot, F.-X., Le Sant, Y., Champagnat, F. and LeBesnerais, G.

"PRINCIPLES AND APPLICATIONS OF PARTICLE IMAGE VELOCIMETRY"

Onera Journal, Issue 1, December 2009, pp. 1- 11.

In this paper, the principles of two-component Particle Image Velocimetry (PIV) and stereoscopic PIV are first recalled. Recent improvements in the camera calibration procedure for stereoscopic PIV are highlighted. The advantages of the PIV technique are illustrated through different studies performed in Onera laboratories for non-reacting flows, and various issues raised by the nature of fluid, flow dynamics, spatial and temporal resolutions, as well as data utilization, are examined. Finally, recent advances in the technique, time-resolved PIV and tomographic PIV, as well as potential gains from novel processing and post-processing algorithms, are presented.

Brousmitche, S.

"SIMULATION OF COHERENT DOPPLER LIDAR SIGNALS AND THEIR ANALYSIS WITH THE COHEN'S CLASS"

PhD Thesis, November 2010, Universite Catholique de Louvain, Louvain-la-Neuve, Belgium.

The problem of wind statistics measurements in the planetary boundary layer using a coherent Doppler LIDAR is addressed. More specifically, it focuses on the design of efficient algorithms in the time-frequency space dedicated to the detection and the characteristics of atmospheric hazards, such as aircraft wake vortices or wind shears. To support this study, a simulation program has been developed which combines the numerical simulation of LASER beam propagation in a turbulent medium with state-of-the-art Large Eddy Simulation (LES) of wake vortex in atmospheric turbulence or in ground effect. This tool constitutes a complete framework for optimizing the LASER source while developing and evaluating the performance of the whole estimation process. Moreover, an analytical formulation of the coherent LIDAR Wigner-Ville spectrum has been derived along with its associated Cohen's class of time-frequency estimators. This theoretical basis leads to explicit equations of the

wind statistics that are retrievable, depending on the measurement conditions and the LASER pulse parameters. It also yields to an adaptive spectral modeling algorithm which is used to detect the wake vortices and then estimate their wind speed probability density function as well as their maximum radial velocity profiles. Another major achievement of this thesis is the development and the validation of a fast inversion method dedicated to wake vortex characterization, e.g., the estimation of its position and intensity. In this method, a Burnham-Hallock model, transformed by a new measurement model integrating the effects of the estimation process, is directly matched to the retrieved radial velocity map. Monte Carlo simulations have been carried out on both analytical models and LES to confirm its good performance. Finally, the validation of the axial detection of vortices with a fiber-based LIDAR has been performed during a test campaign conducted by ONERA at Orly airport in April 2008 during the FIDELIO project. Wake vortex signatures have been successfully obtained with some of the algorithms developed in this thesis.

Brousmiche, S., Bricteux, L., Sobieski, P., Winckelmans, G., Macq, B. and Craeye, C.

"PARAMETERS ESTIMATION OF WAKE VORTICES IN GROUND EFFECT"

15th Coherent Laser Radar Conf., Toulouse, France, June 2009.

In this paper, we propose a method for evaluating the parameters, i.e. core positions and circulation, of wake vortices with a ground-based coherent Doppler Lidar assuming a scanning plane perpendicular to the runway. Its principle is to fit a modified Hallock-Burnham model on the velocity estimates given by the output of a LIDAR simulation module working directly on the velocity space. This simulation uses the results of a computational fluid dynamics simulation of wake vortices in presence of ground effect. The robustness of this method can therefore be assessed when secondary vortices are present in the sensing volume. This model allows us to evaluate how the pulse duration as well as the spatial resolution affects the estimates. The obtained vortex circulations are compared to the exact circulation, as well as to the Gamma 5-15 quantity evaluated on the fluid simulation field. It is shown that the estimation error can vary substantially depending on the position of the vortices and the pulse duration.

Brousmiche, S., Bricteux, L., Winckelmans, G., Macq, B. and Sobieski, P.

"MODELING OF WAKE-VORTEX DETECTION BY A GROUND-BASED FIBER LIDAR SYSTEM"

Advances in Geoscience and Remote Sensors, Chapter 11, Oct. 2009, Intech, pp. 249-268.

The aim of this chapter is twofold. On the one hand, it describes a complete simulation method to evaluate the performance of a Doppler LIDAR for aircraft wake vortices detection near the ground. The principal interest of the simulation presented here is to combine a LASER beam propagation method with fluid dynamics simulations. On the other hand, it proposes effective wind velocity map reconstruction algorithms. The performance of spectral and correlogram accumulation algorithms in the vicinity of wake vortices is analyzed. The effect of velocity gradients on the estimation error is thus addressed.

Brown, A. P.

"WAKE VORTEX CORE PROFILES AND STABILITY FROM ENROUTE FLIGHT DATA"

AIAA Paper No. 2011-3032, June 2011, Honolulu, Hawaii.

Wake vortex core profile and stability characteristics have been analyzed, based upon enroute flight data, gathered upon research flights using the NRC CT-133. The flow field analysis has centered upon the vortex-induced gust velocities measured in the immediate vicinity outside and inside of trailing-pair vortex cores, mildly perturbed in non-turbulent atmospheres, at very large Reynolds Numbers of 2-3 times 1,000,000,000,000, based upon induced windspeed and axial length of the trailing vortices. Vortex-induced core and outside-core profiles were determined by vector-differencing of air and inertial velocity vectors. Kinematic geometry was used to estimate vortex center and radial distance from the center. Core radius was defined by peak vortex-induced velocity. Generally, discrete gust vortex-induced velocity profiles were found to consist of primary, secondary, and tertiary vortex elements. Combinations of primary and secondary elements were prevalent, with peaks of 25 m/s and core radii of 2-6 m, and resulted in sharp-peaked velocity profiles, adequately described by the potential or Rankine vortex model. Occasionally, the profiles were rounded with no secondary or tertiary elements -- such profiles were adequately described by the Burnham-Hallock model. Tertiary vortex elements were small and intense, induced wind speeds and core radii to approximately 35-45 m/s and 0.3-0.6 m, respectively. When normalized, and considered statistically -- about 25% of profiles were of Burnham-Hallock shape with low turbulence levels. The remainder were full-shape profiles: 50% of profiles were between B-H and potential profiles, whilst 25% of profiles had induced velocities greater than potential, of which 5% were greater than twice potential peak velocity. Numerical differentiation of the profiles showed that many of profiles were characterized by a strong Rankine radial mode instability between 0.95 and 1.5 of the vortex core radius. The instability was harmonically mirrored at 2 and 4 times the vortex core radius. Radial analysis indicated that strong, unsteady radial velocities existed for the full-profiles (but not B-H profiles) near core edges and inside cores. The radial flows were both in-flows and outflows. Associated with the inflows was intensification of quasi-vorticity, wherefore spatial gradients of wind gusts were measured under the assumption of frozen-flow, at small scale level.

Brown, A. P.

"THE IMPACT UPON AIRCRAFT AIRWORTHINESS DESIGN FROM ENCOUNTERS WITH DISCRETE VORTICES"

AIAA Paper No. 2006-229, Reno, NV, January 2006

Through the course of the development of aviation, threats to the integrity of aircraft design, as posed by encounters with discrete free vortex flow field structures have generally been realized through bitter experience. Therefore, the engineering response has been, for the most part, reactionary. As an assembly of data, earlier and recent flight research data involving discrete vortex encounters, as conducted by the NRC Flight Research Laboratory, has been reviewed and is presented,

particularly in terms of the parametric variables of the core radius, and vortex strength-to-scale parameter. The flow field characteristics and the aerodynamic loading, flightpath stability and flightpath performance effects upon airplanes encountering the flow fields are categorized and summarized, particularly in relation to current airworthiness and operational requirements. In relation to strength, comparative calculations highlight the shortfall of the classical (1-cos) gust shape, and the complex nature of wake vortex instability scales, wherein substantial loadings, about 0.5g lateral and 2.5g normal, and flightpath disturbances, including roll accelerations of approximately 300 degrees/sec/sec, suggest the generation of smaller scale vortices.

Brown, A. P.

"WAKE VORTEX ENCOUNTER AIRCRAFT AND UNDERWING POD LOADS"

AIAA Paper No. 2012-2673, June 2012, New Orleans, LA.

The NRC CT-133 aircraft has been used for wake turbulence research, over a period of five years. More recently, underwing sensor pod development has been completed, for the conduct of jet aircraft emission flight research, with the intention of being able to fully measure various aspects of emissions holistically, over the whole aircraft wake regimes. Critical airworthiness issues included the loads that the aircraft and pods would be subjected to, in the wake turbulence regimes of wakes, and the trailing-pair wake vortex regime. NRC CT-133 wake turbulence data without the pods has been analyzed and transformed to the pod CG locations, and resulting reactions derived for the pod mounting rack attachment bolt locations, the critical loading points. The resulting pod mounting rack attachment bolt loads have been parametrically related for wake turbulence parameters. When installed, the pods were fitted with accelerometers and accelerations measured, from which loads have been derived. These loads have been compared with those estimated for wake vortex encounter data without the pods. The pods mounting bolts were within the airworthiness safety limit.

Brown, A. P.

"TRAILING VORTEX FORMATION BY LIFTING-LINE FIELD INDUCTION AND CENTRIFUGAL STABILITY ANALYSES"

AIAA Paper No. 2012-2671, June 2012, New Orleans, LA.

Analyses of Wake Vortex formation and downstream development have been conducted, using mutual field induction calculations of the shed vorticity sheet. To illustrate and compare the formation and downstream development of wingtip vortices, the analyses were conducted for two widely-different cases of spanwise distribution of bound-vorticity. Termed inboard and outboard distributions, the loadings were nearly triangular and rectangular, respectively. For development analysis, Biot-Savart field calculations were conducted for the induced velocity field, and hence displacement of the elements of the shed vorticity sheet. Although an induced field calculation does not represent all fluid-element forces (in particular, the expansion pressure field) and thus, might over-estimate core radius for example), the comparative calculations provided results of interest, regarding the properties of

developed wingtip vortices, such as core radius, span location, core asymmetry and peak velocity location. Following this and with reference to the NRC flight measurements of small, intense vortex elements with peaks greater than potential vortex peaks, centrifugal stability analysis is conducted, using a number of models: (1) the developed vortices for the outboard loading case were stimulated with, and released from, radial forcing; (2) a physical model of the centrifugal balance between inertia and pressure forces was examined by time-wise solution of the equations of elemental equations of motion, and (3) the Euler equations in axisymmetric, cylindrical coordinate form were numerically, spatiotemporally solved for excess-velocity vortex profiles. An example of resultant radial flow behavior is compared to flight data.

Brown, A. P.

"WAKE VORTEX CHARACTERISTICS FROM MEDIUM CATEGORY JET TRANSPORTS"

AIAA Paper 2018-2867, June 2018, Atlanta, GA.

In 2017, the NRC undertook biofuel contrail flight research, using Air Canada A320/A321 jet transport aircraft as the contrail generators. In measuring the full contrail cross-section, the NRC CT-133 research aircraft additionally measured the wake vortex characteristics of the aircraft types, Medium Category jet transports. The vortex cores tended to be large, compared to the wingspans, and thus more laterally proximate. Long-wave instability was relatively small wavelength. Short-wave mutual instabilities between vortices exhibited strong excitation of axial vortex velocity components. Cross-plane (orthogonal to the vortex axes) contour plots of vortex parameters, particularly quasi-vorticity, elucidated vortex structural detail. EDR contours were maxima at vortex core edges, some vortex cores were vented, core edges were warm, and core centers cool. Surprisingly perhaps the Brunt-Vaisala frequency contours exhibited stratified, rotating structures to the vortices, delineating Rossby-style spiral structures.

Brown, A. P.

"LINE VORTEX MODELLING OF FREE VORTICES ENCOUNTERED DURING LOW-LEVEL FLIGHT OPERATIONS OVER THE BOREAL FOREST"

AIAA Paper No. 2002-4808, Monterey, CA, August 2002

During BOREAS low-level flight operations, the NRC DHC-6 Twin Otter aircraft of the Institute of Aerospace Research Flight Research Laboratory encountered several discrete large-amplitude thermal gusts, which had an apparent vortical nature to the gust structure, that may be akin to that of other convectively-driven natural vortices, such as 'dust devils'. Assuming a free line vortex model, vertically-aligned, the vortices can be modeled and relevant vortex-aircraft interaction parameters of vortex strength, vortex core radius and vortex-center miss distance identified. This has been conducted for the most severe of the discrete gusts. The identified vortex parameters show the line vortex to be of strength 1315 (meters squared)/s, or that approximately equivalent to the strength of a trailing vortex shed from a wing lifting 10,500 kg mass per meter span at typical takeoff speed, roughly the same

order of magnitude as the effective span loading of the largest widebody design. The vortex core radius was identified as approximately 19 meters and the closest point of approach of the traversing aircraft, about half the core radius. The analysis indicates that the vortex core acted akin to a rotating and vertically-translating 'solid-body', in the upwards transport of high enthalpy momentum. By conducting a traveling 1/2 second sampling window analysis, the 'high frequency' unsteadiness in derived air velocity has been studied. So defined, turbulent velocity components show magnitudes which are proportional to the vortex-induced tangential velocity magnitude, and peak at the edge of the vortex core at values of 10-15%. Inside the core, the turbulence drops linearly. Approximate cross-plane vorticity, estimated by differencing along the flightpath within the core, displays an annular or doughnut distribution of magnitude, with a peak of about 6.7 s at about 80% core radius, thence reducing to about zero at 50% core radius. This might indicate that the vortex core was in a temporally-decaying state and that if so, temporally-maturing thermal vortices, by comparison with other line vortices, might have smaller relative core sizes with greater induced velocity magnitudes and greater hazards to low-flying aircraft.

Brown, A. P.

"AN ENGINEERING STUDY OF THE UNSTEADY RESPONSE OF A JET TRANSPORT DURING A WAKE ENCOUNTER IN A TRANSITIONAL STATE OF POTENTIAL CROW INSTABILITY"

AIAA Paper No. 2002-4715, Monterey, CA, August 2002

An engineering study has been conducted into the unsteady motion and loads response of a widebody jet transport encountering a vortex wake from a preceding 'heavy' aircraft, the wake undergoing a transitional change of flow-state from a trailing-pair through a Crow instability mechanism to a train of vortex rings. It is postulated that, having formed, the migratory Crow instability vortex rings have then rotated to the more stable upright position (coaxial with the downwash vector). The second aircraft is assumed to follow a flight path through the vortex cores of the right side of the vortex rings at 260 knots. On this flight path the estimated strength of the vortex rings is such that the induced velocity produces sideslip angle excursions to plus/minus 10 degrees, with extremely dynamic reversals, up to 200 degrees per second. Accounting for sideslip, lateral and yaw accelerations, the fin loads have been estimated using indicial functions. A yaw damper operating on a simple rate law is calculated to slightly reduce the responsive motion, albeit with a mild increase in fin loads. If reactive pilot rudder inputs are assumed, the analysis indicates that, depending upon sensory/system input-output lag, it could be possible to couple the rudder activity in-phase to each subsequent vortex ring encounter - in which case, significant magnification of fin loads is estimated to occur, of the order of 30-35% greater than that estimated without reactive, dynamic rudder input commands. For the subject transport aircraft, this would represent peak load values of the order of twice the estimated critical design maneuver limit load case.

Brown, A. P.

"THE ALLEVIATION OF WAKE VORTEX ENCOUNTER LOADS, A STUDY OF FLIGHT RESEARCH DATA"

AIAA Paper 2014-2337, June 2014, Atlanta, GA.

Wake vortex encounters, occurring in air transport operations, involve substantial loads, which can result in aggravated flight-path upsets. In order to explore flight control system design for alleviation, the alleviatory effects of conventional flight control surface deflections, upon wake vortex encounter loads has been examined. For this, data was gathered during NRC T33 wake turbulence flight research, of Heavy and Super Category jet transports engaged in enroute operations. Comparative data consists of stick-fixed wake vortex encounters and manually-applied alleviatory control inputs to conventional flight control surfaces. For the alleviatory control-input case, the inputs are experience-based, fully-learned, in other words categorized as instinctive. As such, they were of a high frequency-band, for manual control inputs. Thus, they represent a close-to-limit ability to alleviate wake vortex encounter loads, for the T33 with manual control inputs. The reduction in loads between the two cases, stick-fixed and stick-alleviatory was of the order of 50-60 percent. Given the greater bandwidth of digital flight control systems, it is reasonable to speculate that a wake vortex loads alleviation of significantly greater than 50 percent could be possible with a digital flight control system, based upon the appropriate flight control laws.

Brown, A. P.

"WAKE VORTEX CONSIDERATIONS IN THE ANALYSIS OF RECORDED DATA FROM THE UPSET TO FLIGHT AC190"

LTR-FR-289, Feb. 2008, National Research Council Canada, Ottawa, Canada

Analysis has been conducted of the recorded data of the flightpath upset experienced by Flight AC190, an A319 in scheduled service, in relation to the possibility of having encountered the wake vortex generated by a B747-400 aircraft, approximately ten nautical miles ahead of, and 650 feet above, Flight AC190. The data parameters recorded by the Flight Data Recorder were reviewed and assembled by the Transportation Safety Board, for NRC analysis. The NRC analysis consisted of estimation of incidence and sideslip angles, the derivation of the perturbed wind field, open path integral and circulation estimation, frequency domain analysis of the derived wind field and coherence analysis between pilot flight control commands and aircraft state. In addition, the derived wind field was compared with that experienced by the NRC Falcon 20 aircraft during a flightpath upset following entrainment into the wake vortex flow field generated by a B747-400 aircraft, during an NRC wake vortex research flight.

Brown, A. P.

"FLIGHT DATA OF AXIAL FLOWS IN WAKE VORTEX INSTABILITY"

AIAA Paper 2016-3435, June 2016, Washington, DC.

NRC wake vortex flight research using the CT-133 has included several hundred wake vortex core traverses from a wide range of contemporary Heavy Category wake-generating jet aircraft, measuring a variety of instability modal states of trailing vortices. The long-wave instability of a trailing vortex pair is

a clearly identified and relatively well understood mode, in isolation at least. However, an understanding of short period modes and potential interactions of such modes with the long-wave mode has remained elusive. Prevalent short period modes observed in flight have included forward-facing funnels of axially-varying core radius and vented cores, occasional rear-facing funnels, concentrations of vorticity into annular 'necklace' vortices, and 'sausage-type' axial stretching and contracting of vortex cores. Short period modes have been measured, to have high axial spatial gradients of flow velocity, core radius and vorticity concentration. During research flights measuring emissions from the NRC Falcon in 2015, very intense axial flows were measured at a wave length of approximately 25 wingspans. Axial velocity magnitudes were measured to be the same order as those of cross plane velocity components, with pressure expansions of -2.5 kPa and heating of +5 degrees C. The spatial scale of cross plane vortex-induced flow was much reduced from a nominal core radius of approximately one meter, implying a localized intensification of vorticity and axial inter-change of moments.

Brown, A. P.

"ON THE SPECIFICATION OF WAKE VORTEX ENCOUNTER GUST-FIELDS FROM FLIGHT DATA"

AIAA Paper No. 2010-7678, Toronto, Canada, August 2010.

Wake vortex encounter flow field data has been analyzed for vortices generated by Heavy and Super Category jet transports in enroute cruise, using research flight measurements. The NRC CT-133 was used for the purpose. The flow field analysis has been centered upon the vortex-induced gust velocities measured in the immediate vicinity outside and inside of trailing-pair vortex cores, mildly perturbed to varying degrees in non-turbulent atmospheres, at very large Reynolds Numbers. Analyses used consisted of rise-and-fall analysis of turbulent gusts, continuous turbulence power spectral analysis, and discrete gust analysis. Power spectral analysis indicated that the gust-field intensity did not exceed existing continuous turbulence design standards for a typical Medium Category transport mass and size. However, discrete gust size, shape and magnitude exceeded existing standards. Generally, discrete gust vortex-induced velocity profiles consisted of primary, secondary, and tertiary vortex elements. Combinations of primary and secondary elements were prevalent, with peaks of 25 m/s and core radii of 2-6 m, and resulted in sharp-peaked velocity profiles, adequately described by the potential or Rankine vortex model. Occasionally, the profiles were rounded with no secondary or tertiary elements - such profiles were adequately described by the Burnham-Hallock model. Tertiary vortex elements were intense, up to 32 m/s at core radii 0.3 m.

Brown, A. P.

"GUST LOAD-LINE ANALYSIS RESEARCH OF WAKE VORTEX ENCOUNTER FLIGHT DATA"

AIAA Paper No. 2010-0518, Orlando, FL, January 2010.

In a search for improvements in airport and air route operational capacity, an acceptable level of wake turbulence encounter could be considered -- perhaps by comparing wake vortex encounter (WVE)

upsets with discrete turbulent gust design requirements, for which transport aircraft are certificated, a priori. Such a study has been conducted. Analysis of wake vortex encounters from DAS, DFDR and QAR recorded flight data from research aircraft and commercial aircraft encountering inflight upsets from wake vortex encounters has been used successfully to estimate the detailed characteristics of the upset wind field normal, lateral and axial gust components, in body axes, experienced by the aircraft. The body axis gust components are correlated against the gross loads experienced by the WVE aircraft, in time-domain based Lissajous cross-plots. The cross-plots are compared with the design gust-loads estimated by the CAR 4b and early FAR 25 gust load-line design requirements, for 12.5c '1-cosine' discrete gusts. Comparisons are conducted for a range of WVE aircraft. Agreement with FAR 25 gust load-line estimations is generally quite good, although they disclose concurrent multi-axis gust experiences, with at least one-axis at exceedance magnitude, in the simultaneous presence of autopilot or human-pilot induced maneuver loads, nor in the presence of pilot-induced-maneuver loads. A digital FBW system airplane with gust alleviation is shown to effectively handle WVE loads.

Brown, A. P.

"ANALYTICAL APPROACH TO WAKE VORTEX AND JET WAKE FLOW INTERACTION IN CRUISING FLIGHT"

AIAA Paper No. 2010-0519, January 2010, Orlando, FL.

An analytical approach has been taken, to the cross-plane nature of wake vortex and jet wake flows from commercial heavy jet transports in cruise, with a view to providing insight into the condensation patterns observed visually and sensed by ground-based LIDAR during flight research campaigns by the NRC, DLR and others. For this study, the essential features of the engine-exhaust turbulent jet flow have been considered, amidst the roll-up of the shed vorticity sheet, from the spanwise lift distribution, into a pair of primary, wingtip vortices. Jet-flow entrainment analysis yielded a mass-balancing radial inflow of such a magnitude to be a second-order effect. The buoyant nature of the jet-core airflow from the gas-generator of turbofan engines, used on large jet transport airplanes constituted the principal effect. The degree of mixing between the hot core-flow and the cold bypass jet exhaust flow within the engine installation contributes to the magnitude of buoyancy. In particular, the mixing fraction will be greater in the case of podded-engine installation designs, which mix exhaust streams within the nacelle, compared to a nacelle which does not result in any hot and cold exhaust stream mixing until before discharge into the atmosphere. It is shown that for a hot-stream core-flow exhaust gas temperature of 650 degrees C, upon discharge to the atmosphere in the case of a non-pre-mixed jet-flow, the core-flow detrains from the surrounding cold-stream jet, to rise above and remain above the shed vorticity sheet, essentially non-entrained, whereas the cold flow jet is entrained by the wrapping vorticity sheet. On the other hand, for a 40 percent hot/cold stream pre-mixing in the engine pod, the warmer core-flow detrains initially, but subsequently is re-entrained downwards under wingtip vortex inducement. Both cases have been observed to occur in the contrails of flight observations.

Brown, A. P. and Bastian, M.

"FLIGHT MEASUREMENT OF ENROUTE CONFIGURATION WAKE VORTEX CHARACTERISTICS: A FEASIBILITY STUDY"

AIAA Paper No. 2005-0261, Reno, NV, January 2005

The Flight Research Laboratory has undertaken a feasibility study into obtaining inflight measurements of wake vortex flow fields generated by jet transport airplanes in enroute configuration. The objectives of the study included the establishment of air traffic procedures for the usage of jet transports in commercial service as wake generators, the usage of condensation wake conditions for delineation of wake vortex regions, and the usage of FRL-developed air data and inertial data instrumentation for the accurate identification of wake vortex state parameters from the relatively small wind perturbations induced by the trailing vortices, whilst sampling around the perimeter of the delineated condensation wake domain. Using the NRC Falcon 20 as the wake sampling airplane, the study was conducted in two phases. The first phase studied wakes of length 1-6nm. The second phase, presently reported, studied wakes from 5 to approximately 30 nm in length. The proof-of-concept of the techniques was satisfactorily demonstrated. Condensation wake domains enabled the visual identification of the characteristic upper and lower vortex structures and instability states, and wind perturbations enabled the identification of some vortex characteristics. Results are presented, including examples of vortex strength dissipation, wake descent rates, and the details of several flightpath disturbances induced by close encounters with the trailing vortices.

Brown, A. P. and Bastian, M.

"A FEASIBILITY STUDY ON THE INFLIGHT MEASUREMENT OF ENROUTE WAKE VORTEX CHARACTERISTICS"

AIAA Paper No. 2004-5366, Providence, RI, August 2004

The wider application of RVSM airspace and the emphasis upon the reduction in terminal airspace occupancy times by individual arriving and departing airplanes is tending towards a greater potential for experiencing wake turbulence encounters, where the wake generator is a jet transport in the enroute configuration, either within terminal airspace at an airspeed of 210-250 knots or greater, or whilst climbing/cruising at a Mach Number of 0.7 or greater. It is desirable to obtain controlled flight-measured wake vortex data on enroute configuration wake states and flow-field characteristics. To assess the feasibility of obtaining such data using a sampling airplane undertaking coordinated flights with commercial jet transport wake generators, an internally funded program of measurement has been conducted. The program is based upon: (1) usage of the NRC Falcon airplane as the wake vortex flow-field sampling airplane, with high fidelity air data and inertial data sampling, for the high fidelity resolution of wind components; (2) the prevalence of condensation wake conditions, for visualizing the wake flight-path and state condition; (3) the measurement of vortex-induced wind-flow components (around the vicinity of the trailing vortices, but not necessarily through the vortices) over wake lengths of 30 nautical miles and longer; and (4) usage of a commercial jet transport (B-727-100C) as a wake generator.

Brown, A. P. and Bastian, M.

"OBSERVATIONS OF WAKE VORTEX INSTABILITY FLOWFIELDS AND AIRCRAFT RESPONSE TO ENCOUNTERS"

AIAA Paper No. 2006-6002, Keystone, CO, August 2006

The Flight Research Laboratory (FRL) of NRC Aerospace has undertaken wake vortex flight measurements of wake vortex flow fields generated by jet transport airplanes in enroute configuration, initially aimed at proof-of-concept validation using the NRC Dassault Falcon 20 airplane, for which a two-phase approach was adopted. The first phase observed wakes of length 1 to 6 nm or a normalized time from 0.5 to 3. The second phase, studied wakes from 5 to approximately 30 nm in length or a normalized time from 1 to 6. Sampling was conducted at 32 Hz. More recently, the NRC CT-133 airplane, with 600 Hz sampling air and inertial data systems, has conducted an additional data gathering flight against enroute jet transports. Through the course of all flights, a variety of condensation wake conditions prevailed, with condensation intensity and longevity varying between the upper engine exhaust jet wake and the lower trailing pair vortex wake domains. The sampling airplane conducted helical flightpaths around, rather than through, the condensation flow regimes. However, following the onset of significant multi-wavelength long-period instability (at enroute speeds, generally beyond 6 nm wake lengths), several entrainments of the Falcon 20 into wake vortex cores occurred. The effects of wake vortex core entrainments upon aerodynamic loading, flightpath stability and systems operation have been of particular interest.

Brown, A. P. and Bastian, M.

"ENROUTE FLIGHT DATA OF WAKE VORTEX CORE PROFILES AND PROPERTIES FROM YAWED TRAVERSES"

AIAA Paper No. 2012-2670, June 2012, New Orleans, LA.

Over the period 2006 to 2012, the NRC enroute wake vortex flight research project has measured vortex core profiles and properties, during numerous traverses of the vortex cores generated by Heavy and Super Category jet transports, flying enroute in cruise. The vortex core traverses were conducted by the NRC T-33 and were all initiated in-trail, with the T-33 flight-path being parallel to the vortex core axis -- generally vortex core entries were made in the vortex core six o'clock position. Core traverses took 3/4 to 1 1/4 seconds, over which the T-33 flew along the vortex axis a distance of 200-300 meters, and 4-20 m across the cores, amounting to traverse angles of 2-4 degrees. The vortex core profile symmetry and/or constancy over such a small traverse angle was ascertained by comparing the advancing and retreating segments (to the closest point-of-approach, CPA) of the profiles. Often the implied symmetry/constancy was good, sometimes it was not. Small, very energetic secondary and tertiary vortex segments were encountered only to or from the CPA, on either the advancing or retreating segment. In particular, they made identification of vortex core funnel segments difficult. In 2011, yaw traverses of vortex cores were conducted, entering the cores at angles of yaw to the vortex axial direction, of 15-30 degrees, and/or angles of pitch of c.5 degrees, so that the cores were traversed

over much smaller axial distances than in-trail traverses. The analysis of the flight data from these yaw core-traverses is presented.

Brown, A. P. and Bastian, M.

"WAKE VORTEX FLIGHT MEASUREMENTS AND TACTICAL AIRCRAFT WVE DESIGN & FLIGHT TESTING REQUIREMENTS"

AIAA Paper 2008-1651, February 2008, Los Angeles, CA.

The NRC has undertaken re-instrumentation of the NRC CT-133 ruggedized research airplane, for high altitude atmospheric research. In the process, a new air data system has been designed, and optimized for high data acquisition rates, in particular matching the capability of the aircraft's FRL inertial reference and navigation system, to derive and acquire wind vector data at 600 Hz. The platform has been used to conduct transport aircraft wake vortex (WV) surveys, and acquire instability wake vortex flow field data, most recently in comparative straight flight and turning flight maneuvers, using a Falcon 20 wake generator, to 3 nm distance. Vortex core traverse analysis has highlighted a greater frequency of small-scale vortex segments with high (greater than 150 percent exceedance of the primary vortex) tangential velocities in turning flight. Also, there was a greater bandwidth in short-wave instability wavelengths, and higher amplitude in long-wave instability, and also multi-wavelength, but centered at 3 to 5 generator wingspans, whether in straight or turning flight. Such observations and general considerations of possible tactical jet aircraft wake vortex flow fields suggests the need to establish from flight data, wake vortex flow field environmental design requirements, in order that contemporary and new tactical aircraft types may be developed with robust flight control systems, able to handle the [frequency amplitude] environments experienced during wake vortex encounters.

Brown, A. P. and Bastian, M.

"WAKE VORTEX CORE FLOWFIELD DYNAMICS AND ENCOUNTER LOADS IN-SITU FLIGHT MEASUREMENTS"

AIAA Paper No. 2008-468, Reno, NV, January 2008

The NRC has undertaken re-instrumentation of the NRC CT-133 ruggedized research airplane, for high altitude atmospheric research. In the process, a new air data has been designed, and optimized for high data acquisition rates, in particular matching the capability of the aircraft's FRL inertial reference and navigation system, to derive and acquire wind vector data at 600 Hz. The platform has been used to conduct wake vortex surveys, and acquire WV flow-field data. Vortex core traverse analysis has highlighted a limited number of encounters with vortex elements of circulation to core radius relationships well in exceedance of the general reduction in vortex strength with smaller core radius, typically found in turbulent atmospheric vortex flow-fields. For these encounters, the relationships approached the characteristic relationship of a funnel vortex, in which core radius reduces at constant circulation, so that the circulation to core radius ratio is significantly greater. These observations support the condensation appearance of funneling segments within the WV cores. The core traverse

surveys have provided the opportunity to obtain WV encounter loads data for a small jet encountering vortex wakes in-trail, in cruise. The loads data did not show a consistent decay with wake length (age).

Brown, A. P. and Bastian, M.

"IN-SITU MEASUREMENTS OF ENROUTE CONFIGURATION WAKE VORTEX SCALAR FIELD CHARACTERISTICS"

AIAA Paper No. 2007-289, Reno, NV, January 2007

The scalar fields of vortex-pair-induced pressure, temperature and velocity magnitude from the NRC wake vortex inflight measurement proof-of-concept program are presented for an inbound B767-300 wake of vortex strength of approximately 350 meters squared per second (wake age 1/2 to 1 minute), an outbound B747-400 wake of vortex strength of approximately 600 meters squared per second (wake age 1 to 1.5 minutes), and the vortex core characteristics of an inbound A310 wake of vortex strength of approximately 430 meters squared per second. Correspondence between induced temperature and pressure fields indicated that the fields were representative of near-adiabatic compression or expansion. Between the two wakes the scalar fields exhibited similarities and differences in characteristics, possibly attributable to differences in wake ages/lengths. Similarities were the existence of generalized areas of temperature and pressure rises above the vortex pairs and temperature and pressure reductions in the immediate vicinity of vortex core edges, and between the vortex pair. Differences were notably the lack of distinction of vortex core delineation, in the case of the B747-400 wake and different asymmetries in the scalar fields. Possibly the former was attributable to the greater age, length, and state (near to vortex-linking) of the B747-400 wake. However, the differences in asymmetry were probably attributable to background atmospheric flow field differences. In particular, the B767-300 wake existed in a strong crosswind shear from the right, within which the vortex pair appeared to roll, with the downwind vortex displaced and stretched upwards. From a vortex core transect of the left vortex of the A310 at a wake length of 6 nm (wake age 0.77 min.), internal core-flow features of significance have been identified.

Brown, A. P. and Bastian, M.

"DERIVATION OF WAKE VORTEX CIRCULATION FROM FLIGHT DATA USING PATH INTEGRALS"

AIAA Paper No. 2007-286, Reno, NV, January 2007

In 2003/2004 NRC Aerospace conducted a wake vortex flight measurement proof of concept program, aimed at the demonstration of the cost-effective data gathering of wake vortex flow-field characteristics from jet transports in commercial service. Survey flying consisted of helical flight paths around condensation-delineated wake vortex flow fields. Instrumentation consisted of inertial and air data systems capable of the high-fidelity derivation of wind perturbations for the identification of the flow-field characteristics of trailing pair vortex circulation, separation, axis orientation, descent path and perturbation state. For such identifications, the technique of trial-and-error kinematic fitting of the derived wind perturbations in the time domain was used. In regions of highly-perturbed vortex states,

with attendant highly dynamic flight attitude changes and possibly frequent but poorly-defined vortex core passages, a time domain kinematic fitting process lacked accuracy. Rather, moving-crossplane, open path, and contour path integral methodologies are proposed and applied. Whilst the association between contour path integrals of induced velocity fields and the enclosed field total circulation is well understood (an application of Stokes' Theorem), the relationship between open path integrals of induced velocity and the induced-velocity field motive circulation, and the application thereof to the derivation of wake vortex total circulation, are perhaps less used. Examples from the NRC wake flight measurement program are provided. The usage of open path integrals provides insight into planning optimal wake vortex flight measurement profiles, in order to maximize the effective data return per task flight hour.

Brown, A. P., Bastian, M. and Canteenwalla, P.

"CONTRAIL FLIGHT DATA FROM A VARIETY OF JET FUELS"

AIAA Paper 2018-3188, June 2018, Atlanta, GA.

In 2017/18, the NRC undertook biofuel contrail flight research from several jet transport aircraft and jet fuels, including petroleum JetA1, JP-5, HEFA and ethanol-derived ATJ biofuels. The flight contrail data, consisting of derived ice particle number, size, spherical mass, and the FSSP-100 optical properties of effective size, extinction coefficient, optical depth, and laterally-integrated optical depth, was obtained and compared for JetA1, JP-5 and biofuels (43 percent HEFA-SPK blend with Jet A1 and 92 percent ethanol-derived ATJ-SPK blend with aromatics). Contrail conditions covered sublimating to persistent. Contrail properties were compared with aerosol and non-volatile particulate emissions, and with previous soot modeling of young contrails. Results showed progressive reduction in persistent contrail ice particle number with biofuel blend percentage, almost log-linear reductions with non-volatile aerosol emissions, a slight increase in ice particle size with 92 percent ATJ-SPK. The lateral integrands of optical depth showed 30-50 percent reductions for the 92 percent blend ATJ-SPK, compared to Jet A1.

Brown, A. P., Mokry, M. and Bastian, M.

"FLIGHT MEASUREMENTS OF WAKE VORTEX CIRCULATION IN CROSSFLOW SHEAR"

AIAA Paper No. 2007-285, Reno, NV, January 2007

NRC Aerospace has conducted flight measurements of the wake vortex flow fields of heavy jet transports. Reduction of B767-300 and B747-400 wake vortex flow-field flight data has been conducted. Contour path integrals have been used for the identification of net vortex circulation of the wake vortex trailing pair domain within the cross-plane flightpath contours and of the combined wake vortex trailing pair and jet wake (upper) domains of the wake, within larger flightpath contours. Thereafter, the derived circulations of the domains, which include the inherent circulation of the non-frozen background crossflow windshear, have been examined as functions of mean vertical crossflow windshear magnitude, or crossflow vorticity in the absence of any significant background vertical wind.

The derived circulation was approximately zero for the crossflow vorticity. Dependence upon cross flow vorticity was observed to be much greater than the variation of circulation with wake length. For the B767-300, derived circulation of the trailing vortex pair, including inherent background shear circulation, was about 400 m squared per s at a cross-plane vorticity magnitude of 0.35/s. For the combined wake vortex and jet wake domain, circulation was approximately 1000 m squared per s at a cross-plane vorticity magnitude of 0.020/s, again including the background shear circulation. Data-set standard deviations were approximately 100 m squared per s. As an endeavor to remove the inherent circulation of the background crossflow shear, the mean crossflow wind profiles were regressed to estimate the shear strength, and the circulation calculated for each contour path integral, for the assumed frozen shear. This was subtracted from the wake vortex and wake vortex plus jet wake circulation, to estimate the net circulation of the vortex flow fields. The so-estimated net circulations were approximately zero at a crossflow vorticity of about zero, rising a mean 150 m squared per s for a crossflow vorticity of 0.036/s, with no effective difference between wake vortex net circulation and wake vortex plus jet wake net circulation. There was no significant difference in net circulation for positive (crosswind speed increasing with height) or negative (crosswind speed reducing with height) vertical crossflow shear.

Brown, A. P., Ovenden, M. and Bastian, M.

"A FLIGHT STUDY OF UNSTEADY AERODYNAMIC LOADING INDUCED BY WAKE VORTEX ENCOUNTER"

AIAA Paper 2018-3023, June 2018, Atlanta, GA.

The NRC CT-133 research jet has been installed with a wing glove on the mid-span of the port wing. The wing glove has been installed with pressure transducers, for the measurement of unsteady surface pressures. In flight test, the wing glove has been applied to low-speed stalling and high-speed Mach buffet maneuvers. The wing glove has been applied to the measurement of unsteady lifting loads during wake vortex encounters (WVE), and appeared to faithfully represent surface flow conditions representative of the loading state experienced by the overall aircraft. Local Mach Number on the glove achieved 1.4, without the occurrence of significant shock-induced boundary layer separation (nor, buffet by the overall aircraft), evidential of an increase in the lifting capability of a wing section, under the energizing effect of wake vortex interaction with the wing boundary layer.

Brown, A. P., Politis, E. and Othman, A.

"LINE VORTEX MODELLING OF VORTICES ENCOUNTERED AS TAKEOFF WINDSHEAR BY A WIDEBODY JET TRANSPORT"

AIAA Paper No. 2003-5384, Austin, TX, August 2003

During the airborne phase of takeoff of a widebody jet transport, windshear was encountered. The airspeed increased about 40 knots shortly after liftoff, followed by an approximate 40 knot reduction, concurrent with a wind direction veer from northeast to southwest. The windshear alerting system activated at the completion of the wind veer and airspeed decay. The windspeed data trace from the

digital flight data recorder displayed characteristics that could be represented by an encounter with a discrete vortex of substantial size, followed by a train of encounters with moderately-sized vortices. It is postulated that the data is evidence of a traverse through an atmospheric shear layer consisting of a train of vortices of varying strengths. Simple line vortex models are assumed for each of the principal vortices. Accordingly, the DAR horizontal wind data and derived vertical wind data along the takeoff flight path has been parameter matched to discrete vortex train characteristics of vortex strength, core-axis separation distance, azimuthal vortex axis crossing angle, vortex axis elevation and ground-point origins for each vortex. Following the identification of the azimuthal-crossing and elevation angles of the largest vortex, 17 degrees and 26 degrees respectively, the angles are assumed to be the same for all other discrete vortices in the train. The strength of the largest has been identified as 36,000 ft²/sec (3346 m²/sec) at a vertical separation distance of 400 ft above the aircraft at the path-crossing point. The other discrete vortex strengths have been identified as varying between 4000 and 8000 ft²/sec (372 and 744 m²/sec). The shear intensity from the vortex-induced flow exceeded the 'must alert' cautionary and warning alert thresholds of the TSO-C117a design standards for windshear alerting and guidance systems, which are based upon downburst flow fields.

Brown, C.

"ON THE AERODYNAMICS OF WAKE VORTICES"

AFOSR-TR-72-1209, October 1972, Hydronautics Inc., Laurel, Maryland.

The effect of wing span loading on the development of fully rolled up wing trailing vortices is discussed. It is shown that parabolic wing loadings produce potential flow maximum core rotary speeds which are finite and less than 50 percent of the downwash speeds at the plane of symmetry. The development of turbulent cores is analyzed and core growth is predicted to occur as the two thirds power of time whereas the peak velocities fall off as the inverse one third power. Axial flow effects of the wing profile drag and lifting system are shown to lead to axial jets on the vortex axis which may either follow the aircraft or exceed the free stream velocity depending on the ratio of profile drag to induced drag.

Brown, C. E.

"WAKE TURBULENCE IN A WATER ENVIRONMENT"

Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, Air Force Flight Dynamics Laboratory, AFFDL-TM-75-16-FGC, 1974, pp. 43-49

A review of NASA tests conducted in the Hydronautics Ship Model Basin was given along with experiments with a thermally stratified environment. Vortices showed a definite slowing in their descent in a water environment even without stratification; this was probably related to the observed bursting and fringing of vortices. The tests with a stratified environment showed an additional slowing effect on vortex descent; the vortices leveled off sooner and even bounced back up in some cases.

Brown, C. E.

"PRESSURE FIELD OF A VORTEX WAKE IN GROUND EFFECT"

Journal of Aircraft, Vol. 12, No. 2, February 1975, pp. 120-121

The ground pressures under a descending pair of vortices such as might be generated by aircraft either landing or taking off are computed. It is found that as the vortices first approach the ground, only positive pressures are produced; however, as the descent continues the high velocity field of the vortices makes itself apparent in dips to sub-atmospheric pressure which lie closely beneath the vortex center. Nevertheless, a substantial positive pressure hill precedes the path of the vortex as it moves laterally in the 'ground effect'. The level of pressures produced is dependent only on the flight speed, lift coefficient and aspect ratio while the length scale of the pressure distribution is proportional to the span. These results may be useful in the development of systems to monitor multiple aircraft take-off and/or landing operations.

Brown, C. E.

"THE USE OF SHIP MODEL BASINS FOR THE STUDY OF VORTEX WAKE PHENOMENA"

AFOSR-TR-73-0567, March 1973, Hydronautics, Laurel, MD

The basic differences between test in air and in water are discussed relative to the study of aircraft vortex wake phenomena. It is shown that use of large ship model basins is valid for simulation up to critical Mach numbers of flight. Free surface interference is shown to be negligible for tests made at sufficient towing depths and it is concluded that cavitation must and can easily be avoided entirely at typical towing speeds. Effects of Reynolds number mismatch on the test results is analyzed and it is concluded that wing profile drag coefficients should be matched between full and model scale. Finally, consideration is given to the problem of stopping and starting disturbances in towed-model testing.

Brown, C. E.

"AERODYNAMICS OF WAKE VORTICES"

AIAA Journal, Vol. 11, No. 4, April 1973, pp. 531-536

The effect of wing span loading on the development of fully rolled-up wing trailing vortices is discussed. It is shown that parabolic wing loadings produce potential flow maximum core rotary speeds which are finite and less than 50% greater than the downwash speeds at the plane of symmetry. The development of turbulent cores is analyzed and core growth is predicted to occur as the two-thirds power of time, whereas the peak velocities fall off as the inverse one-third power. Axial flow effects of the wing profile drag and lifting system are shown to lead to axial jets on the vortex axis which may either follow the aircraft or exceed the freestream velocity, depending on the ratio of profile drag to induced drag.

Brown, C. E. and Kirkman, K. L.

"SIMULATION OF WAKE VORTICES DESCENDING IN A STABLY STRATIFIED ATMOSPHERE"

FAA-RD-74-116, July 1974, Hydronautics Inc., Laurel, MD

An experimental simulation of aircraft wake vortices descending in a stable atmosphere has shown that the atmospheric stability stops the downward movement and, in some cases, produces a subsequent rebound. The tests were carried out in a large ship model basin using a rectangular planform wing. Lift coefficients of 0.4 and 1.0 were selected and stable atmospheric conditions were obtained by temperature (density) stratification of the towing basin. Test conditions corresponding to Vaisala-Brunt periods of infinity, 109, and 51 seconds were obtained. The model parameters and stability conditions covered the most extreme cases to be expected in full scale flight.

Brown, C. E. and Miller, Jr., E.

"EXPERIMENTAL STUDY OF TRAILING VORTEX WAKES USING A LARGE TOWING TANK"

Tech Report 7105-1, August 1971, Hydronautics, Laurel, MD

An experimental study of the trailing vortex wake behind a 0.03 scale model of a Boeing 747 transport aircraft was carried out in the Hydronautics Ship Model Basin. The experimental equipment and techniques used are described in detail. Data are presented on vortex trajectories, core diameter and growth, and tangential and axial velocity profiles for the cruise and flaps 30 configuration. Distances behind the model equivalent to 3 miles full scale were achieved before disturbances due to stopping the model affected the results. It was concluded that the techniques developed were suitable for studying devices intended to speed vortex decay and that the results to date show good quantitative agreement with full scale observations.

Brown, C. E. and Van Dyke, P.

"HIGH SPEED COMPUTER STUDIES OF VORTEX MOTIONS IN RELATION TO AIRCRAFT WAKE TURBULENCE"

AFOSR-TR-76-0481, January 1976, Hydronautics Inc., Laurel, MD

Computations are presented and compared with experimental data from other sources for basic and advanced problems in aircraft - wake vortex interactions. Results are presented for coalescence of corotation and counterrotating vortex groups and finally a complete high speed computer method is developed for simulating the roll reaction of an aircraft to the wake produced by a large aircraft with flaps deployed. Suggestions for improved experimental approaches are also appended.

Brown, C. E., Van Dyke, P. and Kloetzli, J. W.

"MEASUREMENTS AND ANALYSIS OF THE FORCES ACTING ON A SMALL AIRCRAFT FLYING IN THE UPWASH OF A LARGE AIRCRAFT"

AFOSR-TR-78-0903, April 1978, Hydronautics Inc., Laurel, MD

A study has been made of the forces and moments acting on a small aircraft while it is flying in the upwash field adjacent to and behind the wing tip of a larger airplane. Preliminary analysis of the expected ranges of forces and moments were made using available theoretical methods and confirming experiments were performed in the Hydronautics Ship Model Basin. The tests used a large model of the Boeing 747 transport aircraft and a smaller model typifying a fighter-type aircraft. The range of positions of the small model relative to the large model extended laterally 30 full-scale feet from the wing tip or from the tip vortex and downstream roughly 80 feet behind the wing tip. Consideration was given to the problem of maintaining steady position at a point that provided a maximum increase in the lift to drag ratio (L/D) of the small aircraft. The model tests have shown that an increase of 50% in L/D can be obtained by a small fighter-type aircraft fling close to the tip trailing vortex of a larger aircraft. Higher increases in L/D for the same relative aircraft positions would result if the smaller aircraft exhibited higher performance (maximum L/D was 8.9 in free air). Calculations made for the models tested indicate that control power of typical fighters would be sufficient to maintain level flight in the favorable positions close to a tip vortex. No influence of the small aircraft on the large should be felt because the most favorable locations for the small aircraft are well behind the wing tip of the large aircraft.

Brown, D. W., Constant, G. D. J., Eacock, J. R., Foord, R. and Vaughan, J. M.

"HEATHROW MEASUREMENTS: WINTER 94/95"

Final Report, October 1995, Defence Research Agency, Malvern, UK

The DRA (Malvern) Lidar has been used to record the wake vortices of nearly 2,000 aircraft on approach to Heathrow. The measurements have been made in a wide range of atmospheric conditions and from five different sites near the airport. This report describes the measurements and presents analyses of a small sample of the data. Different characteristics of the vortices of different aircraft have been observed, and the records include many examples of persistent vortices with ages well over 60 seconds. In at least one case, a vortex returned to the glideslope with undiminished strength 70 seconds after its generation. A detailed analysis of the large amount of data gathered, and correlation with meteorological and other parameters, is continuing.

Brown, G. L. and Lopez, J. M.

"AXISYMMETRIC VORTEX BREAKDOWN, PART 2, PHYSICAL MECHANISMS"

J. Fluid Mech., Vol. 221, December 1990, pp. 553-57.

The physical mechanisms for vortex breakdown which, it is proposed here, rely on the production of a negative azimuthal component of vorticity, are elucidated with the aid of a simple, steady, inviscid,

axisymmetric equation of motion. Most studies of vortex breakdown use as a starting point an equation for the azimuthal vorticity (Squire 1960), but a departure in the present study is that it is explored directly and not through perturbations of an initial stream function. The inviscid equation of motion that is derived leads to a criterion for vortex breakdown based on the generation of negative azimuthal vorticity on some stream surfaces. Inviscid predictions are tested against results from numerical calculations of the Navier-Stokes equations for which breakdown occurs.

Brown, R. E.

"ROTOR WAKE MODELING FOR FLIGHT DYNAMIC SIMULATION OF HELICOPTERS"

AIAA Journal, Vol. 38, No. 1, January 2000, pp. 57-63

A computational helicopter rotor wake model, based on the numerical solution of the unsteady fluid-dynamic equations governing the generation and convection of vorticity through a domain enclosing the helicopter, has been developed. The model addresses several issues of specific interest in the context of helicopter flight dynamic modeling. The problem of excessive numerical dissipation of vortical structure, common to most grid-based computational techniques, is overcome using a vorticity conservation approach in conjunction with suitable vorticity-flux limiter functions. Use of a time-factorization-type algorithm allows the wake model to avoid the stiffness that is introduced in flight dynamic applications by the disparity between the rotor and fuselage timescales and to generate rapid solutions to the time-varying vortical structure of the helicopter wake. The model is demonstrated to yield valid solutions to the blade loading and wake structure for isolated and interacting rotors in both hover and forward flight.

Brown, R. E. and Line, A. J.

"EFFICIENT HIGH-RESOLUTION WAKE MODELING USING THE VORTICITY TRANSPORT EQUATION"

AIAA Journal, Vol. 43, No. 7, July 2005, pp. 1434-1443

Computational fluid dynamic models, through their fundamental treatment of the flow physics, present a unique and powerful tool for analyzing the aerodynamics of helicopter rotors. Their effectiveness is often limited though by difficulties in retaining the structure and form of the rotor wake that result from their tendency to dissipate vorticity. The vorticity transport model, developed some years ago, addresses the problem of vorticity diffusion by solving the fundamental fluid dynamic equations in vorticity conservation form. A development of the original model is described that results in a more efficient computational implementation. The new model uses an adaptive grid system to increase grid resolution significantly, with minimal impact on computational cost. The new grid system is effectively boundary free, thus eliminating the need for numerical boundary conditions at the edges of the computational domain. In addition, the new grid system allows very efficient evaluation of the velocity field using a technique based on the Cartesian fast multipole method. The implementation of both the grid system and the velocity calculation is described, and the performance of the new model is validated against some well-known experimental data.

Brown, R. E., Leishman, J. G., Newman, S. J. and Perry, F. J.

"BLADE TWIST EFFECTS ON ROTOR BEHAVIOUR IN THE VORTEX RING STATE"

European Rotorcraft Forum, Bristol, England, September 2002

Results are shown that give a better understanding of the factors that influence the initiation and subsequent development of the vortex ring state (VRS). It is suggested that the onset of VRS is associated with the collapse of the orderly structure of the rotor wake into a highly disturbed, irregular, aperiodic flow state. An analysis of the stability of the wake is presented to show that the location of the boundary of the VRS is influenced by the detailed structure of the rotor wake prior to its breakdown. Time-accurate calculations of the evolution of the rotor wake in the VRS are then presented to obtain more insight into the flows experienced by the rotor in the VRS. These calculations suggest that the location of the boundary of the VRS, and the depth of the VRS regime, is sensitive to the blade spanwise loading distribution, which is influenced by blade twist. The effects are significant even at low disk loading, but at high thrust where rotor stall may be encountered, rotors with and without significant blade twist show marked, and somewhat counterintuitive, differences in their behavior under VRS conditions.

Brown, S. N.

"THE COMPRESSIBLE INVISCID LEADING-EDGE VORTEX"

Journal of Fluid Mechanics, Vol. 22, Part 1, 1965, pp. 17-32.

The conically symmetric solution of the Eulerian equations of an incompressible fluid obtained by Hall, thought to be descriptive of flow properties in a leading-edge vortex, is generalized to include the effects of compressibility.

Brown, S. N. and Stewartson, K.

"ON COMPRESSIBILITY EFFECTS IN TIP VORTICES"

Proceedings IUTAM Symposium on Concentrated Vortex Motions, July 1964, Ann Arbor, Michigan.

The conically symmetric solution of the Eulerian equations of an incompressible fluid obtained by Hall, thought to be descriptive of flow properties in a tip vortex, is generalized to include the effects of compressibility. The governing equations have an energy integral, and the flow must be homentropic. Some comments are made about the solution when the Mach number of the flow at the outside edge of the vortex is small.

Browning, K. A. and Wexler, R.

"THE DETERMINATION OF KINEMATIC PROPERTIES OF A WIND FIELD USING DOPPLER RADAR"

Journal of Applied Meteorology, Vol. 7, February 1968, pp. 105-113.

A technique is proposed for the measurement of kinematic properties of a wind field in situations of widespread precipitation, using a single Doppler radar to sense the motion of the precipitation particles. The technique is an extension of ideas put forward by Probert-Jones, Lhermitte, Atlas, Caton, and Harrold, and is based upon the Velocity-Azimuth Display (VAD) obtained by scanning the radar beam about a vertical axis at a fixed elevation angle. Harmonic analysis of the VAD permits divergence to be obtained from the magnitude of the 'zeroth' harmonic, wind speed and direction to be obtained from the amplitude and phase of the first harmonic, and resultant deformation and the axis of dilatation to be obtained from the amplitude and phase of the second harmonic. Although limitations to the accuracy of this technique are imposed by inhomogeneities in the horizontal distribution of precipitation fall speed and, in the presence of strong vertical wind shear, by elevation angle errors and reflectivity inhomogeneities, the error resulting from these effects can be made acceptably small by scanning at appropriate elevation angles and ranges. An optimum scanning procedure is suggested. A short case study is also presented to support the view that meaningful estimates of mesoscale divergence and deformation can be obtained using this technique.

Bruce, R. J.

"TRAILING EDGE STRIPS TO REDUCE THE DRAG OF SLENDER WINGS"

PhD Thesis, February 1988, Cranfield Institute of Technology, Cranfield, Bedfordshire, UK.

A slender delta is the ideal layout for good supersonic performance but the intense vorticity in the wake creates very high drag during maneuvering and at low speeds. It should be possible to recover some of the rotational energy from the wake by placing small fins in the strong sideways flows under the vortices to provide a thrust. A further development of this idea is to position long slender fins (or trailing edge strips) in the upwards flows around the vortices in the wake. They provide a lift and thrust over a wide CL range without harming the flow over the wing. This thesis traces the development of these strips in a series of low-speed wind tunnel tests. They were found to reduce the lift-dependent drag of a slender wing by 10 to 15 % at moderate angles of attack without penalizing the performance at very high angles of attack or in the cruise. A few inherent stability problems have been identified but ways to minimize them are suggested. During the course of the study the near-wake flow of a slender delta wing has been extensively studied. No supersonic tests have been carried out but the strips can be stored, if necessary, during supersonic flight.

Brucker, C.

"BREAKDOWN OF SPINNING TUBE FLOWS"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

For our studies of turbulent vortex breakdown, a flow channel with a spinning tube was designed, where the swirl is introduced at the entrance by a honeycomb and maintained over the tube length. This provides a solid body rotation within the tube extending nearly over the complete diameter. Variation of the core Reynolds number and the swirl expressed through the Rossby number could be done independently. A diffuser at the end of the tube induces an adverse pressure gradient to promote vortex breakdown. In conclusion, a turbulent slender vortex is generated with a sharply defined core bounded by the spinning tube. In addition, through that the slender vortex core is axially forced by the spinning tube and the radial pressure gradient in the vortex is linear with the radius it let expect increased structural stability of near-axisymmetric modes of vortex breakdown. Therefore, these investigations could help to clarify the mechanism and conditions responsible for transition of the breakdown types and their stability/instability behavior.

Brucker, C.

"SOME OBSERVATIONS OF VORTEX BREAKDOWN IN A CONFINED FLOW WITH SOLID BODY ROTATION"

Flow, Turbulence and Combustion, Vol. 69, 2002, pp. 63-78

The occurrence of breakdown in slender vortex flows as a 'bubble' or 'spiral' pattern depends on the degree of radial deflection of the vortex core from its original axis. A smooth transition from a bubble to a spiral type 'mode' can be forced by inducing a small asymmetric disturbance which led to the conclusion, that the patterns do not represent different fundamental modes of breakdown. The subject presented herein addresses the following question: how does breakdown evolve in a swirling flow in which the vortex core is forced on a straight axis? In addition, what is the effect of turbulent inflow conditions? This type of vortex conditions is achieved in a spinning tube flow. The swirl is introduced at the entrance of the rotating tube with a honeycomb package and maintained by the viscous action in the boundary layer of the spinning tube. A diffuser at the end induces an adverse pressure gradient to force the breakdown. Flow visualization experiments are carried out to characterize the nature of breakdown over a range of different flow conditions. For some selected characteristic stages, detailed velocity fields were obtained using the method of Digital Particle-Image-Velocimetry (DPIV). The results show, that for the range of parameters investigated, breakdown is initiated at Rossby-numbers below a critical value of Ro about 0.6 like those observed in other experiments. The burst part of the vortex has a near axisymmetric slender conical shape containing approximately stagnant flow. Its downstream end is characterized by a jump-like contraction where the flow evolves into a jet with enhanced swirl on the axis. It is only in this region downstream of the jump-like contraction that asymmetric instabilities and wavy flow patterns could be observed. Perturbations caused by them travel upstream but do not change the near-axisymmetric shape of the burst part of the vortex.

Brucker, C.

"STUDY OF VORTEX BREAKDOWN BY PARTICLE TRACKING VELOCIMETRY (PTV). PART 2: SPIRAL-TYPE VORTEX BREAKDOWN"

Experiments in Fluids, Vol. 14, 1993, pp. 133-139.

The spiral-type breakdown of a slender vortex was quantitatively investigated with PTV. Multiexposed pictures of the illuminated meridional midplane were processed to obtain the instantaneous 2-D velocity field and vorticity distribution. The periodic change of flow patterns with respect to time is clearly shown in a time-series of pictures. The 2-D velocity fields contained a stagnation point in the midplane located outside of the centerline. Additionally, it was observed that this point rotates around the centerline in the same way as the outer flow. A comparison with measurements of a 'bubble-type' breakdown indicates a strong similarity to the spiral-type breakdown. The results reveal that the slope, winding end diameter of the spiral vortex cores determine the different observable forms. The first part of the deflected vortex core near the breakdown point causes an asymmetric backflow due to induction, the strength of which depends on the slope of the deflected vortex core. This is responsible for the radial distance between stagnation point and centerline. In case of the observed bubble-type breakdown the spiral is compressed which results in a stable stagnation point at the centerline.

Brucker, C. and Althaus, W.

"STUDY OF VORTEX BREAKDOWN BY PARTICLE TRACKING VELOCIMETRY (PTV). PART I: BUBBLE-TYPE VORTEX BREAKDOWN"

Experiments in Fluids, Vol. 13, 1992, pp. 339-349.

Using a quasi-three-dimensional instantaneous measurement technique, which combines particle tracking velocimetry (PTV) with volume scanning, first quantitative experimental results of the unsteady and asymmetric interior region of vortex breakdown were obtained. The study was carried out in a low-speed flow through a cylindrical tube. A vortex was generated by a set of guide vanes and subjected to an adverse pressure gradient causing its breakdown. By scanning a pulsed illuminated planar laser light sheet, a set of meridional and azimuthal 'cuts' of the flow were obtained. With PTV the recorded particle paths in the 'cuts' were processed to obtain the instantaneous two-dimensional velocity field, mean streamlines and vorticity distribution. Moreover, the three-dimensional shape of the appearing breakdown, visualized with fluorescent dye, was reconstructed from the 'cuts'. The results revealed that the shape of the bubble nearly equals the stream surface of the stagnation point. According to the conditions in the water tunnel a single tilted vortex ring at the open rear part of the bubble dominates the interior flow structure of the bubble as first noted by Sarpkaya. The vortical flow is bulged over the bubble, then restored and intensified at the lower end. The gathered data lead to the conclusion that the vortex axis remains parallel to the centerline.

Brucker, C. and Schroder, W.

"WAKE DYNAMICS OF AXI-SYMMETRIC BLUFF BODIES"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

With the measurement technique of time recording DPIV we obtained detailed quantitative results of the evolution of the velocity and vorticity field in the wake of axisymmetric bluff bodies. Experiments were carried out in a water tank for Reynolds numbers of $Re=500$, $Re=700$ and $Re=1000$ in the transition range from 'regular' to 'irregular' shedding. DPIV-recordings in radial cross-sections at several distances downstream of the bodies allowed us to reconstruct the dynamics of the streamwise vorticity over many shedding cycles. Our results demonstrate that the wake in this regime consists of a double-sided chain of oppositely oriented hairpin-vortices. One side of the chain is formed by the shed vortices while the other side is formed by induced hairpin vortices which are of considerably less circulation. The measurements revealed to the first time a low-frequency modulation of the vortex shedding with a distinct peak in the spectrum at a Strouhal number of about 0.03. This is best to be recognized in the time-variation of the amount of vorticity shed into the wake which we could analyze from our DPIV data. The frequency spectrum revealed that this peak persists even over the entire transition regime. The wake pattern in this 'irregular' shedding regime typically exhibits periodic packets of 3-4 'regular' shedding cycles which are interrupted by phases with less action. This is explained by the interaction of the helical waves in the wake of axisymmetric bodies.

Brune, G. W.

"QUANTITATIVE LOW-SPEED WAKE SURVEYS"

Journal of Aircraft, Vol. 31, No. 2, March-April 1994, pp. 249-255

Theoretical and practical aspects of conducting three-dimensional wake measurements in large wind tunnels are reviewed with emphasis on applications in low-speed aerodynamics. Such quantitative wake surveys furnish separate values for the components of drag such as profile drag and induced drag, but also measure lift without the use of a balance. In addition to global data, details of the wake flow field as well as spanwise distributions of lift and drag are obtained. This article demonstrates the value of this measurement technique using data from wake measurements conducted on a variety of low-speed configurations including the complex high-lift system of a transport aircraft.

Brune, G. W. and Hallstaff, T. H.

"WING SPAN LOADS OF COMPLEX HIGH-LIFT SYSTEMS FROM WAKE MEASUREMENTS"

Journal of Aircraft, Vol. 22, No. 9, September 1985, pp. 831-832

This note presents wake data of a twin-engine transport in a takeoff configuration and outlines a method of calculating wing loads based on well-known concepts that relate loading to the strength of trailing vortices. The measuring system consisted of a single five-hole conical probe (0.25-in. diameter) mounted on a mechanical traverse in the Boeing Transonic Wind Tunnel. The measured test data included total pressure and three components of wake velocity.

Brunet, S., Garnier, F. and Jacquin, L.

"NUMERICAL/EXPERIMENTAL SIMULATION OF EXHAUST JET MIXING IN WAKE VORTEX"

AIAA Paper No. 1999-3418, Norfolk, VA, June-July 1999

This study is a contribution to the understanding and modeling of engine jet dispersion of an aircraft in cruise condition. One presents a three-dimensional direct numerical simulation (DNS) of the interaction between jets and a vortex wake compare to the results of a wind tunnel experiment. The experimental data described herein comprises velocity fields measured by a Laser Doppler Velocimeter (LDV) and mean temperature fields delivered by thermocouples. The DNS is in qualitative agreement with the experiment but inspection shows departures caused by an underestimation of the jet mixing during the first phases of the jet development.

Brunet, S., Garnier, F. and Sagaut, P.

"CROW INSTABILITY EFFECTS ON THE EXHAUST PLUME MIXING AND CONDENSATION"

Proceedings of 3rd International Workshop on Vortex Flows and Related Numerical Methods, ESAIM, Vol. 7, 1999, pp. 66-79

Three-dimensional direct numerical simulation is performed to study the interaction of two engine jets with a pair of trailing vortices. First, a test panel of selected flux limiter has permitted to suppress spurious oscillations of the passive scalar and to enforce its positivity. Then, contours of a passive scalar (or a tracer concentration) are used to investigate the mixing and entrainment processes when the vortex pair goes through sinusoidal instability. The present results show that the dilution of the exhaust plume is less efficient when the flow undergoes this perturbation. However, the rate of mixing appears insensitive to the development of the Crow instability. Furthermore, to study the condensation process, results are presented involving the calculation of the saturation with respect to liquid water. This is performed by post-processing solution fields which provide a qualitative indicator where the condensation occurred in the aircraft wake.

Brusniak, L., Underbrink, J. R. and Stoker, R. W.

"ACOUSTIC IMAGING OF AIRCRAFT NOISE SOURCES USING LARGE APERTURE PHASED ARRAYS"

AIAA Paper No. 2006-2715, Cambridge, MA, May 2006

Increased restrictions on large commercial aircraft noise levels during takeoff and approach have spawned increased interest in the localization of subcomponent noise sources and quantification of their levels. Landing gear are the dominant sources of airframe noise during approach, with additional contributions from deployed slats, flaps, flaperons and so on. Jet noise, of course, dominates during takeoff. The acoustic phased array is a powerful flight test tool for imaging the noise sources on the aircraft. The acoustic phased array is a spatially distributed set of microphones which simultaneously sample the acoustic field. By appropriately time delaying the output of individual microphones, the origin and level of a given noise source can potentially be determined. The success of this approach

depends largely on 1) the actual character of the source (monopole, dipole, etc.), 2) the phased array design, and 3) the array data processing method. This paper focuses on aspects of the latter two areas. The objectives of this paper are to: a) present the flight test benefits accrued using large aperture phased arrays and, b) examine the utility of recently developed array processing methods for quantifying flight test aircraft subcomponent noise source levels.

Bryant, W. H.

"THE NASA/DOT VOLPE TRANSPORTATION CENTER WAKE ACOUSTIC DATA COLLECTION CAMPAIGN AT DENVER INTERNATIONAL AIRPORT"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

Analytical and experimental evidence suggests that a variety of atmospheric phenomena generate acoustic signals that might be exploited to provide some warning of the hazard's presence. Aircraft wake vortices created as a by-product of lift are among these phenomena. Existing knowledge suggests that wakes emit acoustic signals, but at very low frequencies and at low intensities. Preliminary acoustic signal findings from work conducted under the SOCRATES Program and independently by the German Aerospace Center (DLR-Berlin) suggested that an additional data collection experiment was justified to establish a better scientific understanding of the potential of this phenomenon. An experiment was designed to acquire the most pristine acoustic data ever collected to more fully understand the wake acoustic phenomena. Several sensors and equipment were deployed at the Denver International Airport to experimentally investigate the acoustic properties of wake vortices and to increase the scientific understanding of these acoustic signals. The hypothesis upon which this effort was done is that wake vortices generate unique, consistent acoustic signatures that may be exploited to mitigate the adverse effect of wake turbulence on airport operations. The Denver test was conducted during August/September 2003. The wake acoustic sensor for the Denver International Airport test was a 252-element phased microphone array and meteorological instruments to acquire data permitting a more thorough fundamental investigation of the wake acoustics phenomenon. Both pulsed lidar and CW lidars were used to provide an estimate of actual wake behavior. Additionally, a 4-beam SOCRATES wake acoustics research sensor was deployed to assess modifications made to the SOCRATES hardware and signal processing software in the past two years.

Bryant, W., Lang, S., Tittsworth, J. and Darr, S.

"WAKE VORTEX AVOIDANCE SYSTEM"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-175, September 2007, pp. 3357-3369

There is an urgent need to increase airport capacity without building new runways. Aircraft separation based on wake vortex (WV) mitigation significantly affects airport capacity. While the ICAO WV standards established in the 1970's are effective for safety, they are more conservative than

necessary to preserve safety; and thus, unduly reduce airport capacity. The FAA and NASA have developed an integrated, time-phased approach to meet the needs of the aviation community in lessening the impact of wake turbulence on airport operations. The U.S. National Airspace System (NAS) is developing transition plans to evolve from today's operations to a future system called Next Generation Air Transportation System, or NextGen. NextGen goals include a capacity improvement of 2 to 3 times today's system capacity. To achieve this goal, improvements in communications, navigation, surveillance, and weather technologies must be integrated with wake avoidance solutions and ATC and flight deck procedures and tools. In addition, the safety of the total solution must be demonstrable to the stakeholders and regulatory authorities. This paper presents the elements of a Wake Vortex Avoidance System (WakeVAS) and describes the progress made to date in maturing some of its elements and implementing them as evolutionary steps towards NextGen. Key system performance requirements and the process for defining them are presented for some of the matured elements. Less mature elements of a WakeVAS are also described in terms of observed performance characteristics when used in research mode (e.g., LIDARs) as well as fundamental research issues that need to be addressed before these elements can be considered for inclusion in a WakeVAS. Some of this work is being accomplished in cooperation with the European research community. Lessons learned from safety case development for Simultaneous Offset Instrument Approaches and Lambert - St. Louis International Airport (STL) dependent approach procedures are highlighted with insight into their extensibility to more complex solutions such as Wake Turbulence Mitigations for Departures (WTMD).

Brysov, O. P., Shapovalov, G. K. and Soudakova, I. A.

"EXPERIMENTAL INVESTIGATION OF THE VORTEX FLOW STRUCTURE"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 56-67

The paper deals with a new technique for visualizing 3D vortex flows with the aid of thin, long and practically weightless strips of synthetic foil. The methodology is developed for recording the visualization patterns first on the video camera then on the photo film from the display. Examples are given of visualization patterns of vortical and jet flows. Measurements of tangential and axial velocities in the vortex were conducted with the aid of the five-hole probe.

Brysov, O. P., Soudakova, I. A. and Soudakov, G. G.

"EXPERIMENTAL INVESTIGATION OF THE VORTEX WAKE BEHIND A HIGH-LIFT WING"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 39-50

Measurements of the vortex field in the wake behind a wing model were made in TsAGI's wind tunnel T-124. All the three velocity components, static and total pressures were measured. Analysis of the results is presented.

Buchanan, P.

"AVIATION TURBULENCE ENSEMBLE TECHNIQUES"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 14, 2016, Springer International Publishing Switzerland, pp. 285-296.

Global ensemble weather model forecasts have been available over several decades now. Ensemble forecasts allow uncertainties in even short-range forecasts to be quantified. This is achieved through the principle of running several slightly different but equally feasible forecasts. These forecasts can be used to generate probabilities of turbulence indicators exceeding certain key thresholds. Through calibration, these probability forecasts can be used to generate the likelihood of turbulence occurring. It is even possible to combine these probabilities with non-meteorological information (e.g. the purpose of the aircraft flight) to produce impact forecasts.

Buchholz, J. and Smits, A. J.

"UNSTEADY PROPULSION AND WAKE STRUCTURE OF A FINITE ASPECT RATIO PITCHING PLATE"

AIAA Paper No. 2007-128, Reno, NV, January 2007

Thrust performance and wake structure were investigated for a rigid rectangular panel pitching about its leading edge in a free stream. Thrust coefficient was found to depend primarily on Strouhal number St and the aspect ratio of the panel S/C . Propulsive efficiency was sensitive to aspect ratio only for S/C less than 0.83; however, the magnitude of the peak efficiency of a given panel with variation in Strouhal number varied inversely with the amplitude to span ratio A/S , while the Strouhal number of optimum efficiency increased with increasing A/S . Peak efficiencies between 9% and 21% were measured. Wake structures corresponding to a subset of the thrust measurements were investigated using dye visualization and Digital Particle Image Velocimetry. In general, the wakes divided into two oblique jets; however, when operating at or near peak efficiency, the near wake in many cases represented a von Karman vortex street with the signs of the vortices reversed. The three-dimensional structure of the wakes was investigated in detail for $S/C = 0.54$, $A/S = 0.31$, $Re = 640$. Three distinct wake structures were observed with variation in Strouhal number.

Buck, B. K. and Velotas, S. G.

"DEVELOPMENT OF AN AIRCRAFT APPROACH AND DEPARTURE ATMOSPHERIC PROFILE GENERATION ALGORITHM"

NASA/CR-2004-213236, June 2004, AeroTech Research Inc., Hampton, VA

In support of NASA Virtual Airspace Modeling and Simulation project, an effort was initiated to develop and test techniques for extracting meteorological data from landing and departing aircraft, and for building altitude-based profiles for key meteorological parameters from these data. The generated atmospheric profiles will be used as inputs to NASA's Aircraft Vortex Spacing System (AVOSS) Prediction Algorithm for benefits and trade analysis. A Wake Vortex Advisory System (WakeVAS) is being

developed to apply weather and wake prediction and sensing technologies with procedures to reduce current wake separation criteria when safe and appropriate to increase airport operational efficiency. The purpose of this report is to document the initial theory and design of the Aircraft Approach Departure Atmospheric Profile Generation Algorithm.

Budlong, D. D.

"INTERACTIONS OF AIRCRAFT WAKE VORTICES AND SECONDARY VORTICAL STRUCTURES"

M.S. Thesis, 1999, University of South Alabama, Mobile, AL

The effects of secondary structures on aircraft wake vortices are numerically studied using a three-dimensional point vortex method. This method is first applied to simple vortex structures that have analytical solutions for validation of the computer code, determination of grid resolution requirements, and approximate cut-off distance criteria. Crow instability criteria for three-dimensional counter-rotating vortex-pair is simulated. Vortex rings are used as secondary vortical structures with various circulation strengths, sizes and locations to study the effects of atmospheric turbulence on aircraft wakes. It was determined that the point vortex method in three-dimensional space produced satisfactory results for the validation and Crow instability cases.

Buffo, R. M., Wolf, C. C., Dufhaus, S., Hoernschemeyer, R. and Stumpf, E.

"VORTEX CREATION AND WING-TIP GEOMETRY DEPENDENCIES"

AIAA Paper No. 2012-2770, June 2012, New Orleans, LA.

This study presents experimental 3C-PIV investigations of the vortex topology at the wing-tip. The aim is to identify geometrical aspects of the wing-tip, which exert dominant influence on the production of the axial velocity component. Different wing-tip shapes are considered. Typical rectangular round and flat shapes as well as shapes, which feature a rounding of the layout are used. Special focus is placed upon vortex creation at the wing-tip, where vorticity is accumulated by primary and also to some extent by secondary vortices. The evolution and gradual enhancement of the radial circulation profile is displayed. A rounding of the side of the tip results in a more intensive vortex. An interesting rounding of the layout has the opposite effect. Correlation of vortex topology and therefore wing-tip shaping are shown. In a second step a calculation and analysis of the real, inviscid, as well as the viscous axial velocity component at the center of the vortex is performed. Therefore, the geometrical features of the tip can be related to the production and suppression of the axial velocity component during the vortex creation phase at the wing tip.

Bugala, P. and Dziubinski, A.

"INTERACTION OF HEAVY AIRCRAFT WAKES"

Transactions of the Institute of Aviation, No. 4, 2016, pp. 309-320.

In the next few years, the problem of heavy aircraft wakes may increase on the account of continuous air transport growth. However, it can be noticed that even today the number of accidents resulting from an interaction with wakes is increasing. That is the reason why methods of wake vortex description should be searched for. The aim of this study is to analyze interaction of example aircraft wakes. In this paper the characteristics of vortex wake behind three-dimensional wing are presented. It shows how a separation between aircraft affects the decay of vortex. Two- and three-dimensional calculations were performed using commercial RANS code. The following cases have been taken into consideration: flow past a full commercial aircraft, three-dimensional flow over the simplified wing and a two-dimensional analysis of vortex decay caused by the landing aircraft, including the separation effect. For all these cases a CFD simulation of the aircraft wakes was conducted. One of the main outcomes of this work is a confirmation that the interaction between wakes consists of spreading out and lifting wakes. The achieved results show that the two-dimensional simulation is a sufficient tool for a preliminary analysis of wake vortices. Conclusions from this analysis can be used by the managements of busy international airports to enhance safety.

Bulek, S. and Erdol, N.

"STUDY OF AIRPLANE WAKE VORTEX ACOUSTICS USING BLIND SIGNAL SEPARATION"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

In 2003 NASA and DOT acquired aero-acoustics data by placing a microphone array in the landing path of aircrafts at the Denver International Airport. Our group was charged with developing signal processing algorithms to characterize and isolate any sound associated with a wake vortex. In this paper we report the results of applying a technique broadly known as blind source separation (BSS) to a select number of microphone recordings with the goal of isolating a low power wake vortex sound from the engine and wind noise. We use a multistage approach to deconvolutive BSS on three microphone recordings of aero-acoustic data. The decomposition of the extracted signals into its independent components reveals a structure significantly differentiated from the recorded mix.

Bulek, S. and Erdol, N.

"APPLICATION OF BLIND SOURCE SEPARATION IN THE ANALYSIS OF AIRPLANE WAKE VORTEX ACOUSTICS"

18th International Conf. on Artificial Neural Networks, Prague, Czech Republic, Sept. 2008

Considerations of first principles of fluid dynamics reveal that sounds that are machine generated and sounds that arise from turbulent airflow may be represented as the outputs of linear filters and temporally independent and identically distributed and spatially independent input sequences. These sounds get mixed in the air in an unknown fashion. When we analyze the sound signals in relatively short time intervals, an instantaneous mixing model seems plausible. A blind source separation (BSS) algorithm may then be used to isolate a sound associated with a wake vortex generated by a landing

aircraft. A multistage deflation approach to BSS is applied to four microphone recordings of aero-acoustic data. The decomposition of the observed signals into its independent components reveals a structure significantly differentiated from the recorded mix. Observations also agree with data reported by aviation experts.

Burley, C. L., Brooks, T. F., Rozier, K. Y., van der Wall, B., Richard, H., Raffel, M., Beaumier, P., Deirieux, Y., Lim, J. W., Yu, Y. H., Tung, C., Pengel, K. and Mercker, E.

"ROTOR WAKE VORTEX DEFINITION-EVALUATION OF 3-C PIV RESULTS OF THE HART-II STUDY"

Aeroacoustics, Vol. 5, No. 1, 2006, pp. 1-38

An evaluation is made of extensive three-component (3-C) particle image velocimetry (PIV) measurements within the wake across a rotor disk plane. The model is a 40 percent scale BO-105 helicopter main rotor in forward flight simulation. This study is part of the HART II test program conducted in the German-Dutch Wind Tunnel (DNW). Included are wake vortex field measurements over the advancing and retreating sides of the rotor operating at a typical descent landing condition important for impulsive blade-vortex interaction (BVI) noise. Also included are advancing side results for rotor angle variations from climb to steep descent. Using detailed PIV vector maps of the vortex fields, methods of extracting key vortex parameters are examined and a new method was developed and evaluated. An objective processing method, involving a center-of-vorticity criterion and a vorticity 'disk' integration, was used to determine vortex core size, strength, core velocity distribution characteristics, and unsteadiness. These parameters are mapped over the rotor disk and offer unique physical insight for these parameters of importance for rotor noise and vibration prediction.

Burley, C. L., Brooks, T. F., van der Wall, B., Hughues, R., Raffel, M., Beaumier, P., Delrieux, Y., Lim, J. W., Yu, Y. H., Tung, C., Pengel, K. and Mercker, E.

"ROTOR WAKE VORTEX DEFINITION USING 3C-PIV MEASUREMENTS - CORRECTED FOR VORTEX ORIENTATION"

AIAA Paper No. 2003-3175, Hilton Head, SC, May 2003

Three-component (3-C) particle image velocimetry (PIV) measurements, within the wake across a rotor disk plane, are used to determine wake vortex definitions important for BVI (Blade Vortex Interaction) and broadband noise prediction. This study is part of the HART II test program conducted using a 40 percent scale BO-105 helicopter main rotor in the German-Dutch Wind Tunnel (DNW). In this paper, measurements are presented of the wake vortex field over the advancing side of the rotor operating at a typical descent landing condition. The orientations of the vortex (tube) axes are found to have non-zero tilt angles with respect to the chosen PIV measurement cut planes, often on the order of 45 degrees. Methods for determining the orientation of the vortex axis and reorienting the measured PIV velocity maps (by rotation/projection) are presented. One method utilizes the vortex core axial velocity component, the other utilizes the swirl velocity components. Key vortex parameters such as vortex core size, strength, and core velocity distribution characteristics are determined from the

reoriented PIV velocity maps. The results are compared with those determined from velocity maps that are not corrected for orientation. Knowledge of magnitudes and directions of the vortex axial and swirl velocity components as a function of streamwise location provide a basis for insight into the vortex evolution.

Burnham, D. C.

"WAKE VORTEX SEPARATION REQUIREMENTS FOR THE PROPOSED VERY LARGE AIRCRAFT"

AIAA Paper No. 1999-3422, Norfolk, VA, June 1999

Since the proposed Very Large Aircraft (VLA) is significantly larger than current jet transport aircraft, its introduction may require modification of existing wake vortex separation standards. This paper examines the potential impact of the VLA using two existing safe separation models: one based on wake turbulence encounter reports and the other based on wake decay measurements coupled with an encounter hazard model. The first model predicts that, for the same follower spacing, the encounter rate behind the VLA will be about twice that behind the B-747; hence, increased spacing may be justified behind the VLA. The second model suggests that current spacings are adequate if the VLA is simply treated as a Heavy aircraft. The limitations of the models and their applicability for defining safe separations are discussed.

Burnham, D. C.

"GROUND-BASED WAKE VORTEX SENSOR TECHNOLOGY: CURRENT CAPABILITIES, FUTURE PROSPECTS"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, December 1997, pp. 107-10.

Progress in understanding the behavior of aircraft wake vortices has been dependent upon the development of new measurement technologies. The critical sensor parameters are spatial coverage, location accuracy, capability of assessing vortex strength, unmanned operation, real-time processing, all-weather performance, and cost. Wake vortices have been measured by in-situ wind sensors and virtually all remote sensing technologies (sodar, lidar, radar, and RASS). The status and inherent limitations of these technologies will be reviewed and compared with the requirements for research on wake vortex behavior and operational wake vortex avoidance systems. Note that airborne sensors will not be considered. Suggestions will be made for future sensor development to provide capabilities not currently available. In some cases, a combination of sensors may be more useful than a single sensor for meeting all research/system requirements.

Burnham, D. C.

"REVIEW OF VORTEX SENSOR DEVELOPMENT SINCE 1970"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 47-66

The various sensing techniques developed since 1970 and used for studying aircraft wake vortices are described. The inherent advantages and limitations of each technique are discussed. Emphasis is placed on those sensors used for data collection at airports.

Burnham, D. C.

"CHICAGO MONOSTATIC ACOUSTIC VORTEX SENSING SYSTEM, VOLUME I: DATA COLLECTION AND REDUCTION"

FAA-RD-79-103,I, October 1979, DOT Transportation Systems Center, Cambridge, M.

A Monostatic Acoustic Vortex Sensing System (MAVSS) was installed at Chicago's O'Hare International Airport to measure the strength and decay of aircraft wake vortices from landing aircraft. The MAVSS consists of an array of acoustic antennas which measure the vertical profile up to 60 m altitude of the vertical component of the wind. The decay in wake vortex strength is measured as the vortex passes over successive antennas in the array. This volume describes the MAVSS principles of operation, the hardware developed, and data reduction methods employed.

Burnham, D. C.

"B-747 VORTEX ALLEVIATION FLIGHT TESTS: GROUND-BASED SENSOR MEASUREMENTS"

FAA-RD-81-99, January 1982, DOT Transportation Systems Center, Cambridge, MA

In 1979, a series of B-747 flight tests were carried out to study the wake-vortex alleviation produced by deploying spoilers in the landing configuration. The alleviation achieved was examined by encounters of probe aircraft and by velocity profile measurements made by a ground-based Laser Doppler Velocimeter. For the first time these two types of measurements were analyzed in a way which allowed direct comparison; they showed reasonable agreement. The velocimeter measurements can be used to evaluate the vortex-induced rolling moment on any following aircraft at any separation. The spoiler alleviation was found to be insufficient to assure safe landings of small aircraft at reduced separation behind the B-747. The persistence of the alleviated vortices appears to be due to the wing-tip vortices which dominate the roll-up of the spoiler-alleviated wake. The addition of rapid roll inputs to the spoiler deployment produced much more effective alleviation, but at the expense of an unacceptable ride quality in the generating aircraft.

Burnham, D. C.

"HOW TO USE WAKE VORTEX MEASUREMENTS TO SET SEPARATION STANDARDS"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 53-1 - 53-11

A procedure for setting separations from wake vortex measurements assumes that the current separation standards are 'safe.' A vortex hazard model is used to assess the hazard threshold for vortex strength. Vortex decay measurements are processed to give an empirical model for vortex decay, which specifies the probability of the vortex strength remaining above a given value as a function of vortex age. These two models can be combined to determine the vortex hazard probability at a given separation time. If the hazard probability under current standards for a frequently occurring aircraft pair is defined as safe, then the safe separation for other aircraft pairs can be determined. The sensitivity of the results to the assumed hazard model is then assessed. Two sample applications of this methodology are presented: (1) 2.5-mile separation of small and large aircraft (smaller than the B-757) and (2) reduction of Heavy-Heavy separation from 4 to 3 miles.

Burnham, D. C.

"ANALYSIS OF UK ENCOUNTERS 1982-1990"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 21-1 to 21-4

Wake vortex separation standards are used to limit the frequency and severity of wake vortex encounters under instrument flight rules (IFR). One of the goals of wake vortex research is to develop models that can specify the safe separation for any aircraft pair and hence can be used to judge the safety of proposed changes in separation standards. A direct approach to defining a safe separation model is presented in this paper. The observed UK vortex encounter rates are fitted to a model that defines equal-encounter-rate (EER) separations as a function of the parameters of the leading and following aircraft (specifically their wingspans). Safety is specified by defining the acceptable encounter rate. The first analysis fits the EER separation to powers of the wingspans of the leading and following aircraft. When these powers (1.13 and -0.95, respectively) are found to be close to one, the analysis is repeated using the leader-follower span ratio.

Burnham, D. C.

"NOVEMBER 1996 KENNEDY AIRPORT WAKE VORTEX TEST: SENSOR EVALUATION"

DOT-VNTSC-FA727-PM-27, August 1997, DOT Volpe National Transportation Systems Center, Cambridge, MA

In November 1996, a number of wake vortex and meteorological sensors were operated simultaneously in the middle marker region of Runway 31R at New York's Kennedy Airport. The vortex sensors included: 1) ground-based anemometer array, 2) cw 10-micron lidar, 3) fan-beam sodar, 4) RASS, 5) sonic anemometer, 6) scintillometer, and 7) vertical beam sodar. Comparisons of measurements from the different sensors are presented and used to analyze sensor capabilities and suitability for the NASA Aircraft Vortex Spacing System (AVOSS). Several new observations were made during this test: 1) boundary thickness under the wake vortex in ground effect, 2) high time resolution in situ temperature and velocity measurements inside the vortex recirculation oval, 3) directional

measurements of vortex-generated sound, and 4) the influence of aircraft on meteorological conditions.

Burnham, D. C.

"WAKE VORTEX CIRCULATION MEASUREMENTS"

Third Workshop on Atmospheric Acoustics, York University, Toronto, Canada, June 1975.

An acoustic sounder with separate transmitting and receiving antennas is used to measure the vertical wind profile of an aircraft wake between 20 and 150 feet. The velocity data are processed with correlation techniques to find the vortex locations. The vortex strength and core radius are obtained by fitting the data to a simple model.

Burnham, D. C.

"CHARACTERISTICS OF A WAKE-VORTEX TRACKING SYSTEM BASED ON ACOUSTIC REFRACTIVE SCATTERING"

J. Acoustical Soc. America, Vol. 61, March 1977, pp. 647-654

The theory of acoustic-ray bending by aircraft-generated vortices is developed in a form convenient for application to a practical vortex tracking system. The maximum scattering angle is proportional to the vortex circulation divided by the average core radius. Since the circulation for commercial jet transports is roughly proportional to the wingspan, the value of the maximum scattering angle depends little on aircraft size but strongly on the ratio of the core size to the wingspan. For landing aircraft, the maximum scattering angle varies from 0.5 to 1.4 rad depending upon the engine placement. The capabilities of a pulsed acoustic vortex tracking system depend strongly upon the maximum scattering angle and therefore upon aircraft type. The effects of timing errors, both vortex-induced and random, on tracking accuracy are derived. The fundamental differences between refractive scattering and turbulence scattering techniques are described.

Burnham, D. C.

"EFFECT OF GROUND WIND SHEAR ON AIRCRAFT TRAILING VORTICES"

AIAA Journal, Vol. 10, No. 8, August 1972, pp. 1114-1115

In ground effect, when the wind blows across the aircraft path, one often observes that the up-wind wake vortex consistently descends to a lower altitude than the down-wind vortex. The relationship of this effect to wind shear is illustrated by a simple calculation where the wind shear layer near the ground is modeled as a row of line vortices.

Burnham, D. C. and Abramson, S.

"DATABASE OF GROUND-BASED ANEMOMETER MEASUREMENTS OF WAKE VORTICES AT KENNEDY AIRPORT"

DOT/FAA/ND-97-6, July 1997, DOT Volpe National Transportation Systems Center, Cambridge, MA

A 700-foot array of horizontal and vertical single-axis anemometers was installed at New York's Kennedy Airport on 30-foot poles under the approach to Runway 31R. Although the original purpose for the anemometers was to track the lateral position of wake vortices, new processing algorithms were developed that permit assessment of vortex height and circulation. Data from more than 20,000 landings have been recorded and processed. This report documents the current state of algorithm development and provides processed data for other researchers to analyze.

Burnham, D. C. and Abramson, S.

"WIND DATA FROM MEMPHIS AIRPORT"

DOT/FAA/ND-97-5, June 1997, Scientific and Engineering Solutions, Inc., Orleans, MA.

A 1300-foot array of horizontal and vertical single-axis anemometers was installed at the Memphis, TN, Airport on 10- and 13-foot poles under the approach to Runway 27. One-minute average measurements were recorded continuously from mid-August 1995 through late December 1995. Although the original purpose for the anemometers was to track the lateral position of wake vortices, the measurements also provide a database of wind and turbulence that could be used for other purposes. For example, the crosswind data could be used to evaluate adaptive wake vortex separation systems based on the measured crosswind. The report documents the data formats and database characteristics.

Burnham, D. C. and Greene, G. C.

"WINDOWS-BASED REAL-TIME WAKE VORTEX DISPLAY"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

Real-time wake vortex measurements could improve the safety and efficiency of airport operations. However, no user requirements have been defined, in part because users have never seen real-time vortex tracking. The software presented here was developed to examine optional display formats that will assist users in developing wake vortex sensing requirements. Windline data from DFW, JFK and other airports will be presented.

Burnham, D. C. and Hallock, J. N.

"MEASUREMENTS OF WAKE VORTICES INTERACTING WITH THE GROUND"

j. Aircraft, Vol. 42, No. 5, Sept.-Oct. 2005, pp. 1179-1187

Although wake vortices are known to decay more rapidly near the ground than away from the ground, the details of the ground interaction are not well understood. Propeller anemometer arrays located under the approach path have been used to study vortex transport and provide some information about the vortex interaction with the ground, such as the generation of secondary vortices via boundary-layer detachment. A propeller array at Kennedy International Airport using 8.5-m poles was augmented with 1) a sonic anemometer measuring three-dimensional wind and temperature at 10 Hz and 2) a vertical array of vertical wind and crosswind anemometers, mounted at four additional levels (4.2, 3.2, 1.05 and 0.5 m). The sonic anemometer gave 1) measurements of turbulence inside the vortex flow field and 2) indications of vertical variations in the ambient headwind and temperature, which were brought down to the measurement level by the descent of the vortex recirculation oval. In general, under conditions of low to moderate turbulence, the turbulence level inside the wake vortex flow field is greater than that in the ambient wind. The vertical anemometer array showed that the crosswind profile under a wake vortex in ground effect has a very thin boundary layer, much thinner than that of the ambient wind. It also provided some details concerning the wind profile of the secondary vortex.

Burnham, D. C. and Hallock, J. N.

"WIND EFFECTS ON THE LATERAL MOTION OF WAKE VORTICES"

DOT/FAA/AAR-99/88, November 1999, DOT Volpe National Transportation Systems Center, Cambridge, MA

This report examines the influence of crosswind and other factors on the behavior of wake vortices. Data from acoustic remote sensors and in situ sensors were used to track to possible transport of wake vortices between parallel runways. The measurements used in the analysis came from landing (1976-77) and takeoff (1980) operations at O'Hare International Airport. As expected, wake vortices are observed to transport with the ambient wind; therefore, dangerous wake vortex encounters can be avoided on parallel runways with suitable assignment of aircraft to the two runways. The analyses of the report were carried out in the mid-1980s and serve to document the O'Hare landing and takeoff databases and how they can be used. The status of the acoustic and in situ wake vortex sensors is updated to the late 1990s.

Burnham, D. C. and Hallock, J. N.

"MOTION OF AIRCRAFT WAKE VORTICES IN GROUND EFFECT"

DOT-FAA-AAR-00-16, April 2000, DOT Volpe National Transportation Systems Center, Cambridge, MA

This report addresses the wake-turbulence separation standards for close-spaced parallel runways. Ground-wind anemometer data collected at Kennedy (landing) and O'Hare (takeoff) airports are analyzed to assess the lateral transport probability for wake vortices. A model is developed to predict the lateral transport probability and is used to analyze possible reductions in the wake-turbulence

limits on parallel runways for reduced ranges of aircraft classes (e.g., only small and large aircraft). Unfortunately, adoption of the calculated reduced separation standards cannot be recommended because of uncertainties in the analysis.

Burnham, D. C. and Hallock, J. N.

"WIND EFFECTS ON LATERAL MOTION OF WAKE VORTICES"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

Sodars and/or ground-based anemometers were used to track wake vortices for landing and/or takeoff operations at ORD and DFW airports. The ambient wind was measured by a separate tower (ORD) or the ground-based anemometers themselves (DFW). The study examined the influence of the ambient wind on the probability that vortices generated on one runway can migrate to a parallel runway.

Burnham, D. C. and Hallock, J. N.

"CHICAGO MONOSTATIC ACOUSTIC VORTEX SENSING SYSTEM, VOLUME II: DECAY OF B-707 AND DC-8 VORTICES"

FAA-RD-79-103,II, September 1979, DOT Transportation Systems Center, Cambridge, M.

A Monostatic Acoustic Vortex Sensing System (MAVSS) was installed at Chicago's O'Hare International Airport to measure the strength and decay of aircraft wake vortices from landing aircraft. The MAVSS consists of an array of acoustic antennas which measure the vertical profile up to 60-m altitude of the vertical component of the wind. The decay in wake vortex strength is measured as the vortex passes over successive antennas in the array. In this volume, the data are analyzed to examine whether landing B-707 and DC-8 aircraft need to be divided into heavy and non-heavy categories on the basis of wake vortex hazard.

Burnham, D. C. and Hallock, J. N.

"CHICAGO MONOSTATIC ACOUSTIC VORTEX SENSING SYSTEM, VOLUME III: EXECUTIVE SUMMARY: DECAY OF B-707 AND DC-8 VORTICES"

FAA-RD-79-103, III, January 1982, DOT Transportation Systems Center, Cambridge, MA.

A Monostatic Acoustic Vortex Sensing System (MAVSS) was installed at Chicago's O'Hare International Airport to measure the strength and decay of aircraft wake vortices from landing aircraft. The MAVSS consists of an array of acoustic antennas which measure the vertical profile up to 60-m altitude of the vertical component of the wind. The decay in wake vortex strength is measured as the vortex passes over successive antennas in the array. In this volume, the results of Volume II are summarized in terms of the safety implications of categorizing all landing B-707s and DC-8s as Large aircraft.

Burnham, D. C. and Hallock, J. N.

"CHICAGO MONOSTATIC ACOUSTIC VORTEX SENSING SYSTEM, VOLUME IV: WAKE VORTEX DECAY"

FAA-RD-79-103, IV, July 1982, DOT Transportation Systems Center, Cambridge, M.

A Monostatic Acoustic Vortex Sensing System (MAVSS) was installed at Chicago's O'Hare International Airport to measure the strength and decay of aircraft wake vortices from landing aircraft. The MAVSS consists of an array of acoustic antennas which measure the vertical profile up to 60-m altitude of the vertical component of the wind. The decay in wake vortex strength is measured as the vortex passes over successive antennas in the array. In this volume, the statistical methods used to understand wake vortex decay are described and the data on all common jet transport aircraft are presented.

Burnham, D. C. and Hallock, J. N.

"WAKE VORTEX SEPARATION STANDARDS: ANALYSIS METHODS"

DOT/FAA/ND-97-4, May 1997, DOT Volpe National Transportation Systems Center, Cambridge, MA

Wake vortex separation standards are used to prevent hazardous wake vortex encounters. A 'safe' separation model can be used to assess the safety of proposed changes in the standards. A safe separation model can be derived from an encounter hazard model and a vortex decay model. This report presents subsequent developments and applications of such a model which was first developed in the early 1980s. A static encounter hazard model is coupled with a decay model based on sodar measurements of vortex decay. The separation standards and procedures used from 1976 to 1994 are assumed to be safe based on the absence of IFR accidents. Various versions of the model are used to assess how aircraft should be classified and to evaluate the safety of a possible four-class aircraft separation system. Recommendations are made for ways of improving the safe separation models.

Burnham, D. C. and Hallock, J. N.

"MEASUREMENTS OF WAKE VORTICES INTERACTING WITH THE GROUND"

AIAA Paper No. 1998-0593, Reno, NV, January 1998

Although wake vortices are known to decay more rapidly near the ground than away from the ground, the details of the ground interaction are not well understood. Propeller anemometer arrays located under the approach path have been used to study vortex transport and provide some information about vortex interaction with the ground, such as the generation of secondary vortices via boundary layer detachment. A propeller anemometer array at Kennedy Airport was augmented with (a) a sonic anemometer measuring three-dimensional wind and temperature at 10 Hz and (b) a vertical array of vertical wind and crosswind anemometers, mounted at four additional levels (4.2, 3.2, 1.05, and 0.5 m). The sonic anemometer gave (a) measurements of turbulence inside the vortex flow field and (b) indications of vertical variations in the ambient headwind and temperature. In general, under

conditions of low to moderate turbulence, the turbulence level inside the wake vortex flow field is greater than that in the ambient wind. The vertical anemometer array showed that the crosswind profile under a wake vortex in ground effect has a very thin boundary layer, much thinner than that of the ambient wind.

Burnham, D. C. and Hallock, J. N.

"DECAY CHARACTERISTICS OF WAKE VORTICES FROM JET TRANSPORT AIRCRAFT"

Journal of Aircraft, Vol. 50, No. 1, January-February 2013, pp. 82-87.

In the 1970s the B747-100 alleviation tests, sponsored by NASA with FAA participation, provided unique continuous-wave lidar data, in which the vortex cores could be measured because they were marked with smoke. Measurements for both normal and alleviated wakes showed that the vortex core is persistent whereas the outer circulation of the vortex decays. This form of decay is exactly the opposite of what is observed at low Reynolds number for small aircraft or in wind tunnels. The stability of the core is consistent with the essentially laminar core observed via flow visualization. The circulation profile for the normal wake is well fitted by the Burnham-Hallock model both after initial rollup and after significant decay of the total circulation. The core size for the normal B-747-100 wake is larger (5 percent of wingspan) than typically observed for aircraft with zero or two wing-mounted engines. The observed wake decay means that the total vortex circulation is approximately equal to the popular vortex strength parameter: average circulation over vortex radii from 5 to 15 m.

Burnham, D. C. and Rudis, R. P.

"JFK-1 WAKE VORTEX SENSOR INTERCOMPARISONS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 333-341

Four wake vortex sensors were tested near the middle marker of JFK Runway 31R (aircraft at 50 m height above ground) in November 1996. The status of the sensors and the goals of this test were: (1) cw lidar - relatively mature - reference for vortex location and strength, (2) anemometer array - relatively mature - reference for lateral position - tested height and strength algorithms, (3) RASS - lateral position validated against anemometer array in prior tests - height and strength evaluated against cw lidar, (4) fan-beam sodar - first wake vortex data from final hardware configuration. The performance of each sensor was determined by intercomparisons with measurements of the other sensors for the same vortices. Conclusions were presented on the utility of each sensor technology for the AVOSS system.

Burnham, D. C. and Rudis, R. P.

"EXPECTED PERFORMANCE OF CROSSWIND-BASED WAKE VORTEX AVOIDANCE SYSTEMS AT DFW AIRPORT"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

Relaxation of wake vortex separation standards is possible when the ambient crosswind is within certain limits. The feasibility of a wake vortex avoidance system (WVAS) based on such limits depends upon (1) how often suitable crosswinds occur, (2) how long the conditions last, and (3) whether separation changes can be forecast. The paper analyzes five different crosswind-based WVAS, which address landing, takeoff, single-runway and close-spaced-parallel-runway operations. The analysis uses minute-by-minute wind data collected at the Dallas-Ft. Worth Airport.

Burnham, D. C. and Sullivan, T. E.

"INFLUENCE OF FLAPS AND ENGINES ON AIRCRAFT WAKE VORTICES"

Journal of Aircraft, Vol. 11, No. 9, September 1974, pp. 591-592

Observed differences in aircraft wake vortex core structure are related to engine placement, engine thrust, and wing flap deflection angle. The vortices are divided into two main categories, tubular and non-tubular by two methods: visual observations and results from a pulsed bistatic acoustic vortex sensing system. The major difference is observed in landing configurations between aircraft with and without engines located very close to the outboard flap edge.

Burnham, D. C. and Wang, F. Y.

"DO WAKE VORTICES BEHAVE DIFFERENTLY UNDER NON-LIDAR-FRIENDLY WEATHER CONDITIONS?"

Journal of Aircraft, Vol. 52, No. 3, May-June 2015, pp. 993-996.

No indications were found to suggest that wakes near the ground at San Francisco International Airport might be more hazardous or behave differently under conditions unfriendly to pulsed lidar measurements. Some cases were found where the wake decay was slightly faster under lidar-unfriendly conditions than under lidar-friendly conditions. Thus, pulsed lidar measurements can capture the reasonable 'near-worse-case' wake turbulence hazard near the ground in routine data collection. This study covered many scenarios: 1) two conditions unfavorable for lidar operation (low ceiling and low visibility), 2) several aircraft types, 3) various crosswind conditions, and 4) various headwind conditions. This range of conditions gives confidence in the results.

Burnham, D. C., Clark, K. L., Hallock, J. N., Hannon, S. M., Jacobs, L. G., Rudis, R. P., Soares, M. A. and Wang, F. Y.

"SFO WAKE TURBULENCE MEASUREMENT SYSTEM: SENSORS AND DATA DESCRIPTIONS"

DOT/FAA/AR-07/11, October 2006, DOT Volpe National Transportation Systems Center, Cambridge, MA

This report addresses aspects of an extensive aircraft wake turbulence measurement program conducted at San Francisco International Airport (SFO) over a two-year period. Specifically, this report

describes the sensors used for data collection and the resulting data sets that were used for data collection and the resulting data sets that were used for analysis of the Simultaneous Offset Instrument Approach (SOIA) procedure proposed for use at SFO. Three anemometer Wind lines were deployed perpendicular to and between Runways 28L and 28R to measure and record wake vortex motion between the runways near the threshold and touchdown regions. Because Runways 28L and 28R are used for 80% of SFO arrivals, the SFO wake turbulence Windline dataset, comprising approximately 250,000 arrivals, is the largest ever accumulated. Pulsed lidar wake measurements were made for approximately one month at a location where aircraft were approximately 500 feet above San Francisco Bay (about 9,000 feet from the thresholds). The ambient wind at 20 feet above ground was monitored on either side of the two runways, and a wind Sodar was used to measure wind profiles up to a height of 656 feet. Automated Surface Observation System (ASOS) winds at 33 feet above ground were also obtained.

Burnham, D. C., Gorstein, M., Hallock, J. N., Kodis, R. D., Sullivan, T. E. and McWilliams, I. G.

"AIRCRAFT WAKE VORTEX SENSING SYSTEMS"

DOT-TSC-FAA-72-13, June 1971, DOT Transportation Systems Center, Cambridge, MA

The report summarizes and analyzes techniques, both active and passive, that could be used to detect and measure air movements associated with wingtip vortex generation within an area or throughout a volume of terminal airspace. The study indicates useable techniques with an appraisal of expected performance and inherent limitations. Results of preliminary feasibility tests employing available technology are presented. The report also discusses the systems studies to be performed on the wake vortex sensing problem.

Burnham, D. C., Hallock, J. N. and Greene, G. C.

"INCREASING AIRPORT CAPACITY WITH MODIFIED IFR APPROACH PROCEDURES FOR CLOSE-SPACED PARALLEL RUNWAYS"

Air Traffic Control Quarterly, Vol. 9, No. 1, 2001, pp. 45-58

Because of wake turbulence considerations, current instrument approach procedures treat close-spaced (i.e., less than 2,500 feet apart) parallel runways as a single runway. This restriction is designed to assure safety for all aircraft types under all crosswind conditions. Restricting crosswinds and/or aircraft types can permit safe operations for runways with smaller spacings than 2,500 feet. An alternative safety paradigm can be based on the pairing procedure commonly used for visual approaches to close-spaced parallel runways. In this case, wake turbulence is not a factor if there are appropriate limits on allowed longitudinal pair spacings and/or allowed crosswinds. This paper examines how these concepts can be formulated into safe instrument approach procedures.

Burnham, D. C., Hallock, J. N. and Greene, G. C.

"WAKE TURBULENCE LIMITS ON PAIRED APPROACHES TO PARALLEL RUNWAYS"

Journal of Aircraft, Vol. 39, No. 4, July-August 2002, pp. 630-637

Wake turbulence considerations currently restrict the use of parallel runways less than 2500 feet apart. However, wake turbulence is not a factor if there are appropriate limits on allowed longitudinal pair spacings and/or allowed crosswinds. The tradeoffs between longitudinal spacing and crosswind, needed to prevent wake encounters, are assessed by modeling and by examining wake lateral transport data from O'Hare and Dallas/Ft. Worth airports at distances of 1500 to 3000 feet from runway threshold.

Burnham, D. C., Hallock, J. N., and VanDuyne, E.

"SUMMARY OF WAKE VORTEX SENSOR RESEARCH AND DEVELOPMENT"

Proceedings NASA Wake Vortex Detection Technology Workshop, September 1983, Langley Research Center, Hampton, VA

In this summary paper the status of the wake vortex program from the FAA perspective is reviewed. Special attention is given to the vortex sensor technology as this is an area that NASA may be able to apply expertise gained in other similar programs. This paper first reviews what is and is not known about vortex behavior as one must know its behavior to mitigate its influence. Next, sensors that were developed to collect data on vortex behavior are discussed. Possible problems with an airborne sensor are noted. The paper concludes with a description of the current FAA wake vortex program where short-term solutions are being evaluated as well as the development of long-term research projects.

Burnham, D. C., Hallock, J. N., Kodis, R. D. and Sullivan, T. E.

"VORTEX SENSING TESTS AT NAFEC"

DOT-TSC-FAA-72-2, January 1972, DOT Transportation Systems Center, Cambridge, MA

This report describes the results of a series of tests conducted for the FAA at NAFEC by the DOT/Transportation Systems Center. The test objectives were to determine and evaluate some of the characteristics of three experimental techniques for the remote sensing of the wing-tip vortices generated by heavy commercial and military aircraft. These techniques involved (1) a pulsed, bistatic acoustic detection and ranging system (referred to as an acoustic radar); (2) a ground level pressure sensor; and (3) a ground level hot-wire anemometer. The tests were conducted both in conjunction with the instrumented tower and at the end of runway 13. Data were obtained and analyzed for a variety of aircraft including the DC-7, B-747, C-141 and C-5A. Results in the form of altitudes and times of tower hits and vortex tracks are presented and compared to the tower data wherever possible.

Burnham, D. C., Hallock, J. N., Tombach, I. H., Brashears, M. R. and Barber, M. R.

"GROUND-BASED MEASUREMENTS OF THE WAKE VORTEX CHARACTERISTICS OF A B-747 AIRCRAFT IN VARIOUS CONFIGURATIONS"

FAA-RD-78-146, December 1978, DOT Transportation Systems Center, Cambridge, MA

A Boeing 747 aircraft flew 54 passes at low altitude over ground-based sensors. Vortex velocities were measured by a laser Doppler velocimeter, an array of monostatic acoustic sounders, and an array of propeller anemometers. Flow visualization of the wake was achieved using smoke and balloon tracers and was recorded photographically. Data were obtained on vortex velocity fields, vortex decay, and the effects of spoilers and differential flap settings on the dissipation and structure of the vortices.

Burnham, D. C., Kodis, R. D. and Sullivan, T. E.

"OBSERVATIONS OF ACOUSTIC RAY DEFLECTION BY AIRCRAFT WAKE VORTICES"

J. Acoustical Society, Vol. 52, No. 1, Part 2, March 1972, pp. 431-433

Acoustic ray deflection by aircraft wake vortices has been observed during landing operations by large aircraft. The phenomenon has been used to detect and locate vortex tracks in a plane perpendicular to the runway centerline. The maximum deflection angles observed for a variety of aircraft show qualitative agreement with values predicted for a viscous core.

Burnham, D. C., Rudis, R. P. and Abramson, S.

"PERFORMANCE OF RASS VORTEX DETECTION/MEASUREMENT SYSTEM"

DOT-VNTSC-FAA-99-10, June 1999, DOT Volpe National Transportation Systems Center, Cambridge, MA

Preliminary tests conducted by WLR Research in the Fall of 1993 showed considerable promise that a Radio Acoustic Sounding System (RASS) could detect and tracking wake vortices located in the approach glide slope. Initial testing of the RASS created interest in the possibility of a relatively low cost RASS monitoring the entire approach glide slope out to the middle marker. As a result of the optimistic results of the initial tests, the Federal Aviation Administration Wake Vortex Program Office decided to fund additional testing of the RASS to resolve some remaining questions and to evaluate its performance in detecting wake vortices in both the longitudinal (along the approach path) and transverse (perpendicular to the approach path) modes. The purpose of this test program was to analyze and validate the longitudinal and transverse mode RASS capabilities to: (1) indicate vortex presence in the flight path during a variety of meteorological conditions and (2) track a vortex or pair of vortices during a variety of meteorological conditions.

Burnham, D. C., Sullivan, T. E. and Wilk, L. S.

"MEASUREMENT OF WAKE VORTEX STRENGTH BY MEANS OF ACOUSTIC BACK SCATTERING"

Journal of Aircraft, Vol. 13, No. 11, November 1976, pp. 889-894

A simple acoustic sounder is shown to produce reliable velocity profiles of aircraft wakes at altitudes below 50m. Data collection during normal airport landing operations was feasible because the sensor does not intrude into the airspace being measured. A spatial scan through the wake is obtained when the ambient wind transports the wake through the sounder beam. The data are processed to yield the radial dependence of the velocity and circulation in the wake vortices. The circulation data are fitted to a simple model with two parameters: strength and core radius. The spatial and velocity resolution of the sounder is adequate to measure vortex strength but not to probe details of the core structure.

Burton, G. R.

"ISOPERIMETRIC PROPERTIES OF LAMB'S CIRCULAR VORTEX-PAIR"

Journal of Mathematical Fluid Mechanics, Vol. 7, 2005, pp. S68-S80

Lamb's circular vortex-pair was shown by the author [4] to be the unique maximiser, up to axial translations, of a certain integral functional of the stream function subject to a kinetic energy constraint. The present paper proves that the axial translations of Lamb's circular vortex-pair are the unique maximisers of kinetic energy subject to constraints on the vorticity and impulse. This formulation is more natural, in that it involves only conserved quantities. The result is deduced from [4] by non-convex duality. The analogous theory for Hill's spherical vortex is also discussed briefly.

Bury, Y., Jardin, T. and Klocker, A.

"EXPERIMENTAL INVESTIGATION OF THE VORTICAL ACTIVITY IN THE CLOSE WAKE OF A SIMPLIFIED MILITARY TRANSPORT AIRCRAFT"

Experimental Fluids, Vol. 54, 2013, pp. 1524-1538.

This paper focuses on the experimental characterization of the vortex structures that develop in the aft fuselage region and in the wake of a simplified geometry of a military transport aircraft. It comes within the framework of the military applications of airflow influence on airdrop operations. This work relies on particle image velocimetry measurements combined with a vortex-tracking approach. Complex vortex dynamics is revealed, in terms of vortex positions, intensities, sizes, shapes and fluctuation levels, for both closed and opened cargo-door and ramp airdrop configurations.

Buscher, A., Radespiel, R. and Streit, T.

"MODELLING AND DESIGN OF WING TIP DEVICES AT VARIOUS FLIGHT CONDITIONS USING A DATABASED AERODYNAMIC PREDICTION TOOL"

Aerospace Science and Tech., Vol. 10, 2006, pp. 668-678

A design study of wing tip devices at high and low speeds is described. The basis of the design study is an equivalent drag approach containing both aerodynamic drag gain and structural weight penalty. A comprehensive parameter study is carried out using a rapid aerodynamic prediction tool named Lift

and Drag Component Analysis (LIDCA). Adding to an available lifting-line method a databased module for airfoil data is employed that uses results of two-dimensional flow simulations by multidimensional interpolation. Detailed validation studies of the method at high lift and high speed have demonstrated good accuracy. RANS computations of the selected wing tip designs confirm the predicted benefits at cruise condition. The results of the most effective wing tip designs are analyzed at both flight conditions. Finally, options for improving the performance at take-off are suggested.

Butler, K. M.

"ESTIMATION OF WAKE VORTEX ADVECTION AND DECAY USING METEOROLOGICAL SENSORS AND AIRCRAFT DATA"

DOT/FAA/RD-93/16, September 1993, MIT Lincoln Lab., Lexington, MA

The lift-generated wake vortices trailing behind an aircraft present a danger to aircraft following the same or a nearby path. The degree of hazard to the following aircraft depends on the nature of the wake encountered in its flight path and on the ability of the aircraft to counter its effects. This report describes the current state of understanding of the factors that influence the motion and dissipation of wake vortices. The relationships of these factors to parameters that are measurable through meteorological sensors and from a priori knowledge of the vortex generating aircraft characteristics are discussed as an aid to structuring development plans for the creation of wake vortex advisory products by the Integrated Terminal Weather System (ITWS) and by special wake vortex sensors.

Butler, V. and Poole, Jr., R. W.

"INCREASING AIRPORT CAPACITY WITHOUT INCREASING AIRPORT SIZE"

Policy Study 368, March 2008, Reason Foundation, Los Angeles, CA

The purpose of this policy study is to explore an array of new technologies that hold significant promise for expanding the functional capacity of airport runways. These technologies are planned for incorporation into a completely new air traffic control system to replace the current system over the next 20 years. The wake vortex related topic concerns the construction of new runways between existing runways and using new sensors to detect the motion and decay of wake vortices.

Butoescu, V.

"A VORTEX MODEL OF A HELICOPTER ROTOR"

INCAS - Bulletin, No. 1, 2009, pp. 23-27.

A vortex model of a helicopter rotor is presented. Each blade of the rotor has three degrees of freedom: flapping, lagging and feathering. The motions after each degree of freedom are also known for all blades. The blade is modeled as a thin vortex surface. The wakes are free fluid surfaces. A system of five equations are obtained: the first one is the integral equation of the lifting surface (rotor), the

next three describe the wakes motion, and the last one relates the vortex strength on the wakes and the variation of vorticity on the rotor. A numerical solution of this system is presented. To avoid the singularities that can occur due to the complexity of vortex system, a desingularized model of the vortex core was adapted. A Mathcad worksheet containing the method has been written.

Butsuntorn, N.

"TIME SPECTRAL METHOD FOR ROTORCRAFT FLOW WITH VORTICITY CONFINEMENT"

PhD Thesis, June 2008, Stanford University, Stanford, CA.

This thesis shows that simulation of helicopter flows can adhere to engineering accuracy without the need of massive computing resources or long turnaround time by choosing an alternative framework for rotorcraft simulation. The method works in both hovering and forward flight regimes. The new method has shown to be more computationally efficient and sufficiently accurate. By utilizing the periodic nature of the rotorcraft flow field, the Fourier based Time Spectral method lends itself to the problem and significantly increases the rate of convergence compared to traditional implicit time integration schemes such as the second order backward difference formula. A Vorticity Confinement method has been explored and has been shown to work well in subsonic and transonic simulations. Vortical structure can be maintained after long distances without resorting to the traditional mesh refinement technique.

Butter, D. J. and Hancock, G. J.

"A NUMERICAL METHOD FOR CALCULATING THE TRAILING VORTEX SYSTEM BEHIND A SWEEPED WING AT LOW SPEED"

Aero. Journal, Vol. 75, August 1971, pp. 564-568

A method is presented for the prediction of the spatial distribution of the trailing vorticity during the rolling up process, thus giving the overall downwash field behind the wing.

Butterworth, P. J.

"FLOW MEASUREMENTS IN THE WAKE OF A WING FITTED WITH A LEADING-EDGE ROOT EXTENSION (STRAKE)"

RAE TR-79120, September 1979, Royal Aircraft Establishment, Farnborough, England

In a low-speed wind tunnel measurements have been taken of the velocity vector in the flow field behind the wing of a combat aircraft model. The wing was fitted with a leading-edge root extension (strake) and could have either a plain leading edge or a deployed slat outboard. Four flow investigations were made; at three angles of incidence with the plain leading edge and at one angle of incidence with the slat deployed. The data from each of these tests have been analyzed to give the

distribution of the total head deficit, the streamwise component of vorticity and a measure of the circulation distribution in the wake of the wing.

Butterworth-Hayes, P.

"LANDING IN THE WAKE OF EUROPEAN RESEARCH"

Aerospace America, Vol. 37, No. 6, June 1999, pp. 4-6

European communities have been researching aircraft wake vortices. Germany has been developing the High Approach Landing System/Dual Threshold Operation (HALS/DTS) to reduce aircraft separation distances and maximize runway capacity. A wake vortex (WV) warning system is also under way in Germany, which could result in up to a 33% increase in airport capacity. The U.K.'s National Air Traffic Services (NATS) has been keeping a comprehensive database of WV incidences. The Defence and Research Agency (DERA) was collecting data with a LIDAR earlier in the decade and in 1998. This data will be used to design the Airbus A3XX. The U.K. is also in the middle of a two-year European-wide study, the European Turbulent Wake Incident Report Log (ETWIRL). France has been studying WV's through SYAGE (Système Anticipatif de Gestion des Espacements). The EC is researching WV's through WAKENET and WAVENC as well as through ETWIRL.

Buzykin, O. G., Ivanov, S. V., Ionin, A. A., Kotkov, A. A. and Kozlov, A. Y.

"SPECTROSCOPIC DETECTION OF SULFUR OXIDES IN THE AIRCRAFT WAKE"

Journal of Russian Laser Research, Vol. 26, Number 5, 2005, pp. 402-426.

The absorption/emission spectral regions of SO, SO₂, SO₃, S₂O and HSO are analyzed for the range from UV to IR and are compared with the atmospheric transmission spectrum. It is shown that many vibrational bands of the compounds considered fall into atmospheric transmission windows. For the vibrational bands of SO, SO₂, SO₃ and HSO molecules there are some gases which hinder the absorption diagnostics of the indicated compounds. These interfering gases are natural components of atmospheric as well as specific gases of aircraft engine exhaust. It is found that the least influence of the interference takes place in the 2400-2700 1/cm IR region. The spectroscopic techniques used for the detection of aircraft exhaust compounds are briefly reviewed, with much consideration given to SO₂. The IR absorption spectra of SO₂ and other gases are calculated for the conditions of the aircraft engine nozzle exit. Narrow spectral intervals suitable for SO₂ detection in a hot flow are determined. An analysis is made for the detection capabilities of CO₂ lasers (including isotope CO₂ lasers) and CO lasers (both fundamental band and first-overtone ones) as applied to SO₂ detection in aircraft engine exhaust.

Cabot, M. A. and Chiang, N. Q.

"WAKE TURBULENCE WARNING AND CAUTION SYSTEM AND METHOD"

US Patent 6,177,888 B1, January 2001.

A wake turbulence warning and caution system and method for a protected aircraft tracks and stores a trajectory of a wake trailing behind a nearby aircraft and adjusts the wake position for the effect of local wind velocity, and then calculates a distance and time to closure between the protected aircraft and the wake. A caution is annunciated aurally and/or on a navigation map display and/or on a primary flight display if the distance or time to closure is less than a first predetermined threshold, and a warning is annunciated if the distance or time to closure is less than a second predetermined threshold. The wake trajectory is calculated based on range, bearing, and altitude information about the nearby aircraft supplied by a Traffic Collision Avoidance System (TCAS) aboard the protected aircraft, and based on inertial position and attitude of the protected aircraft supplied by an inertial reference system (IRS). Local wind velocity is calculated based on the aircraft inertial velocity from the IRS, true air speed from an air data computer (ADC), and angle of attack and sideslip angles provided by sensors aboard the aircraft. Wake tracking, wind velocity calculations, and caution and warning functions can be implemented in software within a TCAS computer and/or a flight management system aboard the protected aircraft.

Cai, H. J. and Beyers, M. E.

"OVERVIEW OF ROTARY FLOW VISUUALIZATION RESULTS ON THE F/A-18 AIRCRAFT"

ICAS Paper 2002-3.10.4, September 2002, Toronto, Canada.

To understand the physics of the complex vortex flow field of the F/A-18 aircraft during maneuvering at high incidences, a series of flow visualizations were conducted in the Institute for Aerospace Research 0.38 x 0.51m water tunnel. A 1/72-scale model was tested on the new orbital-platform rotary apparatus at various angles of attack.

Cai, J., Chng, T. L. and Tsai, H. M.

"NUMERICAL STUDY OF VORTICAL FLOWS SHEDDING FROM A BLUFF BODY WITH A WAVY TRAILING EDGE"

AIAA Paper No. 2007-131, Reno, NV, January 2007

Previous experimental studies have shown that applying a geometric sinusoidal disturbance to the trailing edge of a quasi-streamlined bluff body can result in substantial base pressure recovery when compared against a normal straight edged configuration. Here, a numerical simulation at a Reynolds number of 2500 is used to examine in detail various aspects of the flow such as the base pressure distribution, vortex shedding mechanism and frequency selection in relation to a variation in the wavelength of the sinusoidal disturbance. The concentration of dye released along the upper trailing edge of the body is tracked by solving the scalar transport equation to facilitate visualization and comparison of the flow field analogous to the dye precipitation technique used in previous studies. The results show that a sinusoidally shaped trailing edge with fixed amplitude and a wavelength which is 5 times the base height displays a reduction of more than 36% in the mean drag coefficient when

compared to the straight edged case. This reduction is traced to a lengthening of the mean recirculation region, a marked drop in the velocity fluctuation at the dominant frequency of the wake and a reduction in the spanwise component of the wake vorticity. Conversely, this reduction in the drag coefficient is substantially diminished for a sinusoidal trailing edge with a longer wavelength. For such a configuration, the flow is characterized by the formation of vortex dislocations which causes the flow to have a less regular character. Finally, a shorter wavelength of four base heights results in a reduction of the mean recirculation region with an attendant increase in the spanwise vorticity. This leads to a drag coefficient similar to that of the straight trailing edge.

Cai, J., Deng, S., Shan, H., Jiang, L. and Liu, C.

"LES INVESTIGATION OF NEAR FIELD WAKES BEHIND JUNCTURE OF WING AND PLATE"

AIAA Paper No. 2004-0262, Reno, NV, January 2004. (Also, Current Trends In High Performance Computing and Its Applications, Springer Berlin Heidelberg, December 2005)

This paper is a preliminary work on the numerical study of the near field wake and wingtip vortex behind the juncture of wing and plate. The object is to develop a LES-based code to simulate the near field wake and wingtip vortex, which will help understanding near field wakes and wake control. The filtered structure function subgrid model was applied on the simulation. The computational approach involves a fully implicit time-marching solver for the Navier-Stokes equation in the generalized curvilinear coordinates with a sixth order compact scheme and an eighth order filter. A one-block high-quality mesh is generated in the complex computation domain. The coordinate transformation metrics are calculated with the high-order compact scheme that is consistent with the flow solver. The parallel computation is accomplished by using domain decomposition and message passing interface (MPI). The code is validated for simulation of flow transition on a flat plate. The code is also used for simulation of 2-D airfoil vortex shedding. Then the flow field around NACA0014 airfoil is simulated with 8 million grid points. The preliminary results were obtained. To study the near field wake and wingtip vortex behind the juncture of wing and plate, a LES simulation with 25 million grid points is undergoing, in which the angle of attack of the wing is 10 degrees.

Cai, J., Deng, S., Xie, P. and Liu, C.

"HIGH-ORDER LES FOR WING TIP VORTEX IN THE NEAR FIELD"

AIAA Paper No. 2005-1125, Reno, NV, January 2005

The numerical study of wingtip vortex in the near field is presented in this paper. The object is to develop a LES-based code to simulate the wingtip vortex, which will help understanding near field wakes and wake control. The filtered structure function sub-grid model was applied on the LES simulation. The computational approach involves a fully implicit time-marching solver for the Navier-Stokes equation in the generalized curvilinear coordinates with a sixth order compact scheme and an eighth order filter. A one-block high-quality mesh is generated in the complex computation domain. The coordinate transformation metrics are calculated with the high-order compact scheme that is

consistent with the flow solver. The parallel computation is accomplished by using domain decomposition and message passing interface (MPI). The code is validated for simulation of flow transition on a flat plate. The code is also used for simulation of 2-D airfoil vortex shedding. Then the flow field around NACA0012 airfoil is simulated with 25 million grid points. The preliminary results were obtained.

Cai, J., Tsai, H.-M., Luo, S. and Liu, F.

"STABILITY OF VORTEX PAIRS OVER SLENDER CONICAL BODIES - THEORY AND NUMERICAL COMPUTATIONS"

AIAA Paper No. 2004-1072, Reno, NV, January 2004

Theoretical analyses and computational fluid dynamics (CFD) simulations are presented to study the formation and stability of stationary symmetric and asymmetric vortex pairs over slender conical bodies in an inviscid incompressible flow at high angles of attack with and without sideslip. The theoretical analysis is based on an eigenvalue analysis on the motion of the vortices under small perturbations. A three-dimensional time-accurate Euler code is used to compute five typical flows studied by the theoretical method on extraordinarily fine and overset grids with strict convergence criteria. The computational results agree well with the theoretical predictions and corroborate on the conclusion that an absolute type of hydrodynamic instability can be the mechanism for breaking of symmetry of the vortex flow over slender conical bodies at high angles of attack. The presented results demonstrate the usefulness of CFD for stability studies of vortex flow over slender bodies at high angles of attack.

Cai, J., Xie, P., Wei, H. and Liu, C.

"VERIFICATION AND VALIDATION OF LES FOR INTERACTION OF WINGTIP VORTEX AND WAKES"

AIAA Paper No. 2008-673, Reno, NV, January 2008

Large eddy simulation with filtered-structure-function subgrid model and implicit large eddy simulation (ILES without explicit subgrid model) using high-order accuracy and high-resolution compact scheme have been performed on the tip vortex shedding from a rectangular half-wing with a NACA 0012 airfoil section and a rounded wing tip. The formation of the tip vortex and its initial development in the boundary layer and the near field wake are investigated and analyzed in detail. The physics, why the tip vortex, which is originally turbulent in the boundary layer, is re-laminarized and becomes stable and laminar rapidly after shedding in the near field, is revealed by this simulation. The computation also shows the widely used second order subgrid model is not consistent to six-order compact scheme and would degenerate the six-order LES results to second order. Therefore, high order schemes, grid refinement and six order subgrid models are critical to LES approaches.

Caiger, B. and Gould, D. G.

"AN ANALYSIS OF FLIGHT MEASUREMENTS IN THE WAKE OF A JET TRANSPORT AIRCRAFT"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 125-136

Peak velocity vectors measured in the transverse plane of the wake of a Convair 880 aircraft were found to be four times as high as anticipated. The peak velocities are shown to occur in small intense vortices which are separate from the main tip vortices. These exist up to 30 seconds after generation. The main tip vortices are shown to have a core size which is roughly of the size anticipated but whose diameter does not increase significantly up to 30 seconds after generation.

Caillol, P. and Maslowe, S. A.

"THE SMALL VORTICITY NONLINEAR CRITICAL LAYER FOR KELVIN MODES ON A VORTEX"

Studies in Applied Mathematics, Vol. 118, Issue 3, April 2007, pp. 221-254.

We consider in this paper the propagation of neutral modes along a vortex with velocity profile being the radial coordinate. In the linear stability theory governing such flows, the boundary in parameter space separating stable and unstable regions is usually comprised of modes that are singular at some value denoted the critical point. The singularity can be dealt with by adding viscous and/or nonlinear effects within a thin critical layer centered on the critical point. At high Reynolds numbers, the case of most interest in applications, nonlinearity is essential, but it develops that viscosity, treated here as a small perturbation, still plays a subtle role. After first presenting the scaling for the general case, we formulate a nonlinear critical layer theory valid when the critical point occurs far enough from the center of the vortex so that the vorticity there is small. Solutions are found having no phase change across the critical layer thus permitting the existence of modes not possible in a linear theory. It is found that both the axial and azimuthal mean vorticity are different on either side of the critical layer because of the wave mean flow interaction. A long wave analysis with vorticity leads to similar conclusions.

Caisso, P., Valentin, J. C. and Corjon, A.

"SY.A.G.E. - THE FRENCH WAKE VORTEX SPACING SYSTEM"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

The STNA (Service Technique de la Navigation Aérienne) has been performing studies on wake vortices since 1992 for the DGAC (Direction Générale de l'Aviation Civile). Due to limited budget, the work progress is not as fast as expected. In this paper, we present SY.A.G.E. (SYstème Anticipatif de Gation des Espacements). This system intends to optimize the separation between aircraft at landing and takeoff. All the developments done in France are related to this definition. A first version of SYAGE has been set up and an experiment aiming at operationally verifying the system is presented. This first version concerns aircraft at departure and crosswind considerations. A windline of seven anemometers has been installed on Toulouse-Blagnac Airport to monitor the position of the vortices. This trial should assess the needed accuracy of the wind measurement for an operational system. The constituted wind

database will be used to develop short term forecasting compulsory to have in the landing version of SYAGE.

Calarese, W.

"CLOSE-COUPLED CANARD-WING VORTEX INTERACTION"

J. Aircraft, Vol. 21, No. 2, February 1984, pp. 99-100

The present experiment investigates the interaction of canard and wing vortices and their effect on the lifting wing's flow field turbulence and Reynolds stresses. Spanwise wing blowing was used to enhance the leading-edge vortex and alter the vortex trajectory to keep it locked to the wing's leading edge for lift enhancement. The turbulence intensity and Reynolds stress values, obtained by using hot film anemometers, illustrate the vortex structure.

Calhoun, R., Wieser, A., Princevac, M. and Kottmeier, C.

"COMPARISON OF LIDAR DATA WITH TOWER, PROFILER, RADIOSONDE, AND TETHERSONDE DATA"

2nd Symposium on Lidar Atmospheric Applications, 85th AMS Annual Meeting, January 2005, San Diego, CA.

During July 2004, the Institut fuer Meteorologie und Klimaforschung, Tropospheric Section (IMK-TRO), Forschungszentrum Karlsruhe / Universitaet Karlsruhe, Germany, and the Lidar group of Arizona State University (ASU) collaborated to obtain a dataset for the comparison of IMK's new coherent Doppler lidar with data from a radar profiler, a 200m tower, tether sondes, radiosondes, and a sodar. The experiment took place near Karlsruhe, Germany, and was centered at the Forschungszentrum just north of the city of Karlsruhe. All field instruments were provided and operated by IMK, while ASU assisted in planning, post-processing, and some operation of the IMK coherent Doppler lidar and tether sondes. During the experimental period, occasional convective storms passed through the measurement domain providing at times relatively strong wind velocities. Mean and instantaneous velocities were compared between the instruments. In addition to mean velocities, the spectral properties of lidar 'staring' scans were explored. For the 'staring' scans, the lidar beam focused on two levels of the local 200-meter meteorological tower at which sonic anemometers obtained wind data at 20 Hz.

Cali, P. and Drela, M.

"IMPLICIT EULER CALCULATION OF SUPERSONIC VORTEX WAKE/ENGINE PLUME INTERACTION"

AIAA Paper No. 1993-0656, Reno, NV, January 1993. [Also, Cali, P. M., MS Thesis, MIT, Cambridge, MA.]

This paper presents the computational modeling of supersonic vortex wake/engine plume interaction. The evolution of the wake and plume was modeled in the Trefftz plane using the two-dimensional, unsteady Euler equations. The flow was initialized to a vortex sheet with adjacent engine plume and

integrated using a third-order accurate flux-difference-split, implicit algorithm. To minimize the effects of numerical diffusion, a Lagrangian correction technique was retrofitted to the implicit Euler code. Test cases varying the initial spanwise location of the plume were conducted. In all cases, the plume was seen to break apart into small bundles which then orbited the vortex core. Although the inward pressure gradient of the rolled-up vortex drove the hot effluent toward the center, the inward motion of the buoyant plume fluid was limited due to the lack of a diffusive model. Finally, the amount of effluent drawn tightly to the core increased as the initial plume location was moved outward along the span.

Cali, P. M.

"IMPLICIT EULER CALCULATION OF SUPERSONIC VORTEX WAKE/ENGINE PLUME INTERACTION"

MS Thesis, September 1992, Massachusetts Institute of Technology, Cambridge, MA.

This paper presents the computational modeling of supersonic vortex wake/engine plume interaction. The evolution of the wake and plume was modeled in the Trefftz plane using the two-dimensional, unsteady Euler equations. The flow was initialized to a vortex sheet with adjacent engine plume and integrated using a third-order accurate flux-difference-split, implicit algorithm. To minimize the effects of numerical diffusion, a Lagrangian correction technique was retrofitted to the implicit Euler code. Test cases varying the initial spanwise location of the plume were conducted. In all cases, the plume was seen to break apart into small bundles which then orbited the vortex core. Although the inward pressure gradient of the rolled-up vortex drove the hot effluent toward the center, the inward motion of the buoyant plume fluid was limited due to the lack of a diffusive model. Finally, the amount of effluent drawn tightly to the core increased as the initial plume location was moved outward along the span.

Callantine, T. J., Bienert, N., Borade, A., Gabriel, C., Gujral, V., Jobe, K., Martin, L., Omar, F., Prevot, T. and Mercer, J.

"HUMAN-IN-THE-LOOP INVESTIGATION OF INTEROPERABILITY BETWEEN TERMINAL SEQUENCING AND SPACING, AUTOMATED TERMINAL PROXIMITY ALERT, AND WAKE-SEPARATION RECATEGORIZATION"

AIAA Paper 2016-3300, June 2016, Washington, DC.

A human-in-the-loop simulation study addressed terminal-area controller-workstation interface variations for interoperability between three new capabilities being introduced by the FAA. The capabilities are Terminal Sequencing and Spacing (TSAS), Automated Terminal Proximity Alert (ATPA), and wake-separation recategorization, or 'RECAT.' TSAS provides controllers with Controller-Managed Spacing (CMS) tools, including slot markers, speed advisories, and early/late indications, together with runway assignments and sequence numbers, ATPA provides automatic monitor, warning, and alert cones to inform controllers about spacing between aircraft on approach. ATPA cones are sized according to RECAT, an improved method of specifying wake-separation standards. The objective of the study was to identify potential issues and provide recommendations for integrating TSAS with ATPA and

RECAT. Participants controlled arrival traffic under seven different display configurations, then tested an 'exploratory' configuration developed with participant input. All the display conditions were workable and acceptable, but controllers strongly preferred having the CMS tools available on Feeder positions, and both CMS tools and ATPA available on Final positions. Controllers found the integrated systems favorable and liked being able to tailor configurations to individual preferences.

Callegari, A. J. and Ting, L.

"MOTION OF A CURVED VORTEX FILAMENT WITH DECAYING VORTICAL CORE AND AXIAL VELOCITY"

SIAM Journal of Applied Mathematics, Vol. 35, No. 1, 2006, pp. 148-175.

The motion and decay of a vortex filament with large axial and circumferential velocity components in a three-dimensional stream are studied. Solutions are constructed to the Navier-Stokes equations by use of matched asymptotic expansions; the small parameter used is a measure of the ratio of the viscous effects to the vortex strength. The outer flow, which corresponds to the classical Biot-Savart type analysis is matched to the solution in an inner viscous region. The radius of the viscous core is assumed to be much smaller than the radius of curvature. The present viscous analysis yields the classical inviscid theory as a limiting case for the leading term in the outer region and thus can be used to correct various deficiencies in the latter. We show, that the inner solution yields a finite velocity at all points in the filament and we determine how the components of both vorticity and velocity diffuse due to the viscous forces. The matching conditions guarantee the continuity of velocity components and define the velocity of the filament which depends not only on the geometry of the vortex filament but also on the circumferential and axial velocity variations in the inner core.

Calvert, M. E. and Wenren, Y.

"ROTORCRAFT OUTWASH AND HUMAN STABILITY"

AIAA Paper 2019-1095, January 2019, San Diego, CA.

This paper documents an investigation of aerodynamic interactions between rotor design and human stability within the outwash region of hovering rotorcraft. The ability of rotorcraft to hover is a defining feature for rotorcraft, but the resulting downwash and outwash can be hazardous to people within proximity of the most energetic regions of the flow field. Most of the research up to this point has attempted to qualitatively describe the outwash environment in relation to existing rotorcraft. This paper documents an effort to use Design of Experiments with outwash flow-field models to identify characteristics that have the greatest influence on human destabilization. Factors such as rotor design parameters, human anthropometric data, and footwear/surface friction characteristics are assessed to gauge significance for human susceptibility to slipping and toppling. Qualitative parametric trends are identified that can be considered during rotorcraft design and operational planning to decrease the probability of human instability within the rotorwash footprint.

Cambon, C., Godeferd, F. S., Nicolleau, F. C. G. A. and Vassilicos, J. C.

"TURBULENT DIFFUSION IN RAPIDLY ROTATING FLOWS WITH AND WITHOUT STABLE STRATIFICATION"

J. Fluid Mech., Vol. 499, 2004, pp. 231-255

In this work, three different approaches are used for evaluating some Lagrangian properties of homogeneous turbulence containing anisotropy due to the application of a stable stratification and a solid-body rotation. The two external frequencies are the magnitude of the system vorticity, chosen vertical here, and the Brunt-Vaisala frequency N , which gives the strength of the vertical stratification. Analytical results are derived using linear theory for the Eulerian velocity correlations (single-point, two-time) in the vertical and the horizontal directions, and Lagrangian ones are assumed to be equivalent, in agreement with an additional Corrsin assumption used by Kaneda (2000). They are compared with results from the kinematic simulation model (KS) by Nicolleau and Vassilicos (2000), which also incorporates the wave-vortex dynamics inherited from linear theory, and directly yields Lagrangian correlations as well as Eulerian ones. Finally, results from direct numerical simulations (DNS) are obtained and compared for the rotation-dominant case, the stratification dominant case, the non-dispersive case, and pure stratification and pure rotation. The last situation is shown to be singular with respect to the mixed stratified/rotating ones. We address the question of the validity of Corrsin's simplified hypothesis, which states the equivalence between Eulerian and Lagrangian correlations. Vertical correlations are found to follow this postulate, but not the horizontal ones. Consequences for the vertical and horizontal one-particle dispersion are examined. In the analytical model, the squared excursion lengths are calculated by time integrating the Lagrangian (equal to the Eulerian) two-time correlations, according to Taylor's procedure. These quantities are directly computed from fluctuating trajectories by both KS and DNS. In the case of pure rotation, the analytical procedure allows us to relate Brownian t-asymptotic laws of dispersion in both the horizontal and vertical directions to the angular phase-mixing properties of the inertial waves. If stratification is present, the inertia-gravity wave dynamics, which affects the vertical motion, yields a suppressed vertical diffusivity, but not a suppressed horizontal diffusivity, since part of the horizontal velocity field escapes wavy motion.

Cameron, L., Early, J. M., Medina, H. and McRoberts, R.

"AN EXPERIMENTAL STUDY INTO THE TURBULENCE CHARACTERISTICS OF LAMINAR, TRANSITIONAL AND TURBULENT IMPINGING JETS"

AIAA Paper 2011-3085, June 2011, Honolulu, Hawaii.

Particle Image Velocimetry has been utilized to obtain instantaneous velocity fields for water jets impinging perpendicularly on a solid surface. Time-averaged turbulence statistics are presented for laminar, transitional and turbulent jets in the Reynolds number range 3000 - 10000. A vortex identification algorithm is also employed to calculate the probability of a vortex existing at each discrete grid point based on all of the instantaneous fields. Significant turbulent mixing is induced by increasing the Reynolds number from 3000 to 4000, indicating transition commences in this range. The transition onset is characterized by a sudden increase in mean turbulent kinetic and velocity fluctuations as well as the coalescence of small-scale vortices into large scale coherent structures.

Further increasing the Reynolds number results in a decrease in the levels of non-dimensional turbulent kinetic energy in the shear layer implying a lesser proportion of the initial energy possessed by the jet is lost through dissipation resulting in favorable heat transfer characteristics at the impingement surface. The transitional jet with $Re = 4000$ proves to be an interesting case producing a strong wall jet with intense turbulent fluctuations that may result in large heat transfer rates over a greater radial distance.

Campbell, G. S.

"TURBULENCE IN THE WAKE OF A THIN AIRFOIL AT LOW SPEEDS"

NACA TM-1427, 1957, Langley Aeronautical Lab., Langley Field, VA

Experiments have been made to determine the nature of turbulence in the wake of a two-dimensional airfoil at low speeds. The experiments were motivated by the need for data which can be used for analysis of the tail-buffeting problem in aircraft design. Turbulent intensity and power spectra of the velocity fluctuations were measured at Reynolds number of 160,000 for several angles of attack.

Campbell, J. F. and Chambers, J. R.

"PATTERNS IN THE SKY: NATURAL VISUALIZATION OF AIRCRAFT FLOW FIELDS"

NASA SP-514, January 1994, NASA Langley Research Center, Hampton, VA

The objective of the current publication is to present the collection of flight photographs to illustrate the types of flow patterns that were visualized and to present qualitative correlations with computational and wind tunnel results. Initially in section 2, the condensation process is discussed, including a review of relative humidity, vapor pressure, and factors which determine the presence of visible condensate. Next, outputs from computer code calculations are postprocessed by using water-vapor relationships to determine if computed values of relative humidity in the local flow field correlate with the qualitative features of the in-flight condensation patterns. The photographs are then presented in section 3 by flow type and subsequently in section 4 by aircraft type to demonstrate the variety of condensed flow fields that was visualized for a wide range of aircraft and flight maneuvers.

Campbell, J. F., Chambers, J. R. and Ramsey, C. L.

"OBSERVATION OF AIRPLANE FLOWFIELDS BY NATURAL CONDENSATION EFFECTS"

Journal of Aircraft, Vol. 26, No. 7, July 1989, pp. 593-604

Flight condensation patterns illustrate a variety of airplane flowfields, such as attached and separated flows, vortex flows, and expansion and shock waves. Analysis shows vortex cores have a low relative humidity which may help explain the voids in condensed vortex flows.

Campbell, S. D. and Evans, J. E.

"GROUND-BASED WAKE VORTEX MONITORING, PREDICTION, AND ATC INTERFACE"

Airborne Windshear Detection and Warning Systems - Fifth and Final Combined Manufacturers' and Technologists' Conference, DOT/FAA/RD-94/14-II, July 1994, Langley Research Center, Hampton, VA, pp. 569.

Three elements of a proposed Wake Vortex Advisory Service are presented: monitoring, prediction, and ATC interface. The monitoring element is needed to ensure safety by warning controllers of hazardous wake vortex conditions. Such conditions exist when wake vortices persist in the approach/departure flight paths due to advection or to atmospheric conditions which prevent their decay. The prevention element is needed to provide ATC supervisors with advance warning that wake vortex separation conditions are about to change (i.e., require increased or decreased wake vortex separation). The ATC interface is needed to provide controllers with adaptive wake vortex separations. A 10.6-micron CO₂ CW lidar system will be developed for characterizing the behavior of wake vortices in an operational airport setting. Wide-area weather data will be gathered by an Integrated Terminal Weather System (ITWS) testbed. Interface to the terminal ATC system will be accomplished using the TATCA (Terminal Air Traffic Control Automation) Interface Unit (TIU), which would allow wake vortex separation symbology to be inserted onto a TRACON controller's Full Digital ARTS Display System (FDADS) radar screen.

Campbell, S. D., Dasey, T. J., Freehart, R. E., Heinrichs, R. M., Matthews, M. P. and Perras, G. H.

"WAKE VORTEX FIELD MEASUREMENT PROGRAM AT MEMPHIS, TN"

AIAA Paper No. 1996-0399, Reno, NV, January 1996.

This paper describes wake vortex field measurements conducted during August 1995 at Memphis, TN. The objective of this effort was to record wake vortex behavior for varying atmospheric conditions and aircraft types. Wake vortex behavior was observed using a mobile continuous-wave coherent laser Doppler radar (lidar) developed at Lincoln Laboratory. This lidar features a number of improvements over previous systems, including the first-ever demonstration of an automatic wake vortex detection and tracking algorithm. An extensive meteorological data collection system was deployed in support of the wake vortex measurements, including a 150' instrumented tower, wind profiler/RASS (radio acoustic sounding system), sodar and balloon soundings. Aircraft flight plan and beacon data were automatically collected to determine aircraft flight number, type, speed and descent rate. Additional data was received from airlines in post-processing to determine aircraft weight and model. Over 600 aircraft wakes were recorded over the one-month period during 29 traffic pushes. Preliminary results from the field measurement program are presented illustrating differences in wake vortex behavior depending on atmospheric conditions and aircraft type.

Campbell, S. D., Dasey, T. J., Freehart, R. E., Heinrichs, R. M., Matthews, M. P., Perras, G. H. and Rowe, G. S.

"WAKE VORTEX FIELD MEASUREMENT PROGRAM AT MEMPHIS, TENNESSEE: DATA GUIDE"

NASA CR-201690, April 1997, Lincoln Laboratory, Lexington, M.

Eliminating or reducing current restrictions in the air traffic control system due to wake vortex considerations would yield increased capacity, decreased delays, and cost savings. Current wake vortex separation standards are widely viewed as very conservative under most conditions. However, scientific uncertainty about wake vortex behavior under different atmospheric conditions remains a barrier to development of an adaptive vortex spacing system. The objective of the wake vortex field measurement efforts during December 1994 and August 1995 at Memphis, TN, were to record wake vortex behavior for varying atmospheric conditions and types of aircraft. Wake vortex behavior was observed using a mobile continuous-wave (CW) coherent laser Doppler radar (lidar) developed at Lincoln Laboratory. This lidar features a number of improvements over previous systems, including the first-ever demonstration of an automatic wake vortex detection and tracking algorithm.

Campbell, S. D., Dasey, T. J., Heinrichs, R. M. and Matthews, M. P.

"OVERVIEW OF 1994 MEMPHIS WAKE VORTEX TESTING PROGRAM"

Proceedings Sixth Conf. on Aviation Weather Systems, American Meteorological Society, Dallas, TX, January 1995, pp. 515-520

This paper outlined a comprehensive field measurement program for automated collection of wake vortex, atmospheric and aircraft data in an operational airport environment. These measurements will provide a valuable data base to aid in the validation of wake vortex behavior models and techniques for atmospheric diagnosis/prognosis.

Campobasso, M. S., Zanon, A., Minisci, E. and Bonfiglioli, A.

"WAKE-TRACKING AND TURBULENCE MODELLING IN COMPUTATIONAL AERODYNAMICS OF WIND TURBINE AEROFOILS"

Proceedings of the Institution of Mechanical Engineering, Part A: Journal of Power and Energy, Vol. 223, No. 8, 2009, pp. 939-951.

This article addresses two modelling aspects of wind turbine airfoil aerodynamics based on the solution of the Reynolds-averaged Navier-Stokes (RANS) equations. One of these is the effect of an a priori method for structured grid adaptation aimed at improving the wake resolution. The presented results emphasize that the proposed adaptation strategy greatly improves the wake resolution in the far field, whereas the wake is completely diffused by the non-adapted grid with the same number and spacing patterns of grid nodes. The proposed adaptation approach can be easily included in the structured generation process of both commercial and in-house-structured mesh generators. The other numerical aspect examined herein is the impact of particular choices for turbulence modelling on the predicted solution. This includes the comparative analysis of numerical solutions obtained by using different turbulence models, and aims at quantifying the solution inaccuracy arising from not modelling

the laminar-to-turbulent transition. It is found that the drag forces obtained by considering the flow as transitional or fully turbulent may differ by 50 per cent. All these issues are investigated using a special-purpose hyperbolic grid generator and two multi block structured finite volume RANS codes. The numerical experiments consider the flow field past a wind turbine airfoil for which an exhaustive campaign of steady and unsteady experimental measurements was conducted. The predictive capabilities of the CFD solvers are validated by comparing experimental data and numerical predictions for selected flow regimes. The incompressible analysis and design code XFOIL is also used to support the findings of the comparative analysis of numerical RANS-based results and experimental data.

Campos, L. M. B. C.

"ON RUNWAY CAPACITY AND WAKE VORTEX SAFE SEPARATION DISTANCE"

Third SESAR Innovation Days, November 2013, Stockholm, Sweden.

The capacity of ATM is limited by the runway availability at airports. The number of takeoff and landings from the same runway is limited by wake vortex separation distances. Currently the safe separation distances (SSD) are established by empirical rules using as sole criterion the classification of the leading and following aircraft into three weight categories 'light', 'medium' and 'heavy'. The Boeing B757 has been the subject of an exception to the rules increasing the separation distance based on flight incidents; the Airbus A380 has been subject of an extended separation distance for 'super heavy' aircraft as a safety precaution. The purpose of the present paper is to obtain a formula for wake vortex separation distances that involves a number of assumptions and simplifications, but does include more parameters rather than just the weight of the leading and following aircraft. The predicted SSD for pairs of typical light (Citation 500), medium (B737-300) and heavy (B747-400) aircraft are comparable to the ICAO minimum separation rules, suggesting that the latter are moderately conservative on the safe side. The special case of B757-200 is considered justifying the increased separation. In the case of A380-100, the special 'ultra-heavy' rules appear to be excessively conservative highlighting the need for a more scientific approach to the subject, especially in cases where a long experience from the past is not available.

Campos, L. M. B. C. and Marques, J. M. G.

"ON WAKE VORTEX RESPONSE FOR ALL COMBINATIONS OF FIVE CLASSES OF AIRCRAFT"

Aeronautical J., Vol. 108, Issue 1084, June 2004, pp. 295-310

The present paper concerns the response of a following airplane to a pair of wing tip vortices left by a leading aircraft, represented by the Hallock-Burnham model, including the effect of vorticity decay between the two aircraft. The effect of vorticity is evaluated in terms of the induced rolling moment and also the lift loss; these specify the roll acceleration and the downward acceleration, respectively. The corresponding two response equations can be put into the same dimensionless form, and integrated using exponential integrals. This specifies the roll rate and sink rate as a function of time; besides the latter, the bank angle and altitude loss, are also plotted, all also as a function of time, for all

combinations of leading and following aircraft in five classes. These are the three ICAO weight categories of light, medium and heavy, plus two other cases, viz the special case of the Boeing 757, which requires larger separation distances, and the case of a future very large transport aircraft exceeding significantly the size of a Boeing 747.

Campos, L. M. B. C. and Marques, J. M. G.

"ON AIRCRAFT RESPONSE AND CONTROL DURING A WAKE ENCOUNTER"

In Progress in Industrial Mathematics at ECMI 2008, Springer-Verlag, Berlin Heidelberg, 2010, pp. 747-752.

In this paper the exact analytical solution of the airplane response to a wake encounter appears as a power series of a damping factor, whose coefficients are exponential integrals in time. It is shown that in the absence of control action, the roll response tends to an asymptotic bank angle.

Campos, L. M. B. C. and Marques, J. M. G.

"ON AN ANALYTICAL MODEL OF WAKE VORTEX SEPARATION OF AIRCRAFT"

The Aeronautical Journal, Vol. 120, No. 1232, October 2016, pp. 1534-1565.

A theory is presented on the effect of wake turbulence of a leading aircraft on the roll stability of a following aircraft, leading to a simple formula for the safe separation distance between the two aircraft that provides estimates of aircraft separation distances comparable to existing empirical regulations, based on experience. The formula includes the effects of flight and atmospheric conditions, and the characteristics of the leading and following aircraft; it applies to similar or dissimilar aircraft, and it indicates the parameters and conditions leading to increasing or decreasing separation. The formula is applied not only to the three International Civil Aviation Organization (ICAO) categories of aircraft (light, medium and heavy, respectively, Cessna Citation, B737 and B747) but also to 'special' aircraft requiring larger separation distance (Boeing 757) and to the world's largest airliner (Airbus A380).

Campos, L. M. B. C. and Marques, J. M. G.

"ON WAKE VORTEX RESPONSE FOR SEVERAL COMBINATIONS OF LEADING AND FOLLOWING AIRCRAFT"

ICAS-2002-7.9.4, Toronto, Canada, September 2002

The response of a following airplane to a pair of wing tip vortices left by a leading aircraft, represented by the Hallock-Burnham model, with added vorticity decay between the two aircraft. The effect of vorticity is evaluated as concerns the induced rolling moment and the lift loss; these specify respectively the roll acceleration and the downward acceleration. The corresponding two response equations can be put into the same dimensionless form, and integrated using exponential integrals. In the present paper we study the three ICAO weight categories of light, medium and heavy, plus two

other cases, vis-a-vis the special case of Boeing 757, which requires larger separations distances, and the case of very large aircraft, like the VLTA.

Campos, L. M. B. C. and Marques, J. M. G.

"ON THE COMPENSATION AND DAMPING OF ROLL INDUCED BY WAKE VORTICES"

Aeronautical Journal, Vol. 118, No. 12207, September 2014, pp. 1039-1061.

The effect of the wake of a leading aircraft on a following aircraft is demonstrated by calculating the rolling motion consisting of three terms: (i) the free rolling motion due to initial bank angle and roll rate; (ii) the forced wake response due the rolling moment induced by the wake encounter; (iii) the forced control response due to aileron deflection to counter the wake vortex effects. It is shown that in the absence of control action, the roll rate of the following aircraft goes through a peak, and then decays, leading to a constant asymptotic bank angle; the latter is a measure of the magnitude of the wake effect, e.g. is larger for weaker damping. The exact analytical solution of the roll equation appears as a power series of a damping factor, whose coefficients are exponential integrals of time; it is shown that the first two terms give an accuracy better than 2 percent. The theory is used to simulate 15 combinations of wake vortex encounters between leading and following aircraft in the five ICAO/FAA weight categories: light, medium, heavy, special (B757) and very large (A380).

Campos, L. M. B. C. and Marques, J. M. G.

"ON THE EFFECT OF DAMPING AND CONTROLS ON AN AIRCRAFT WAKE ENCOUNTER"

ICAS 2006, Sept. 2006, Hamburg, Germany.

The effect of damping and controls on an aircraft wake encounter is modeled using the following assumptions: (i) the wake of the leading aircraft is represented by a pair of counter-rotating Hallock-Burnham vortices, with arbitrary circulations and core radii; (ii) the vorticity decays with distance due to a turbulent kinematic viscosity, according to a law which is consistent with flight data from the Memphis data base; (iii) the rolling moment induced in the following aircraft is calculated assuming it flies aligned behind the leading aircraft; (iv) the rolling moment equation is solved analytically including the effect of the control surface deflection (e.g., ailerons) and of aerodynamic damping; (v) the airplane response, in terms of roll rate and bank angle is plotted for a Boeing B757-200 flying behind another. It is shown that in the absence of control action, the roll rate of the following aircraft goes through a peak, and then decays, leading to a constant asymptotic bank angle; the latter is a measure of the magnitude of the wake effect, e.g. is larger for weaker damping. The exact analytical solution of the roll equation appears as a power series of a damping factor, whose coefficients are exponential integrals of time; it is shown that the first two terms give an accuracy better than 2 percent.

Campos, L. M. B. C. and Serrao, P. G. T. A.

"ON THE ACOUSTICS OF UNBOUNDED AND DUCTED VORTEX FLOWS"

The propagation of sound is considered in a potential cylindrical vortex, with superimposed axial flow, by means of explicit analytical solutions. The sound waves are sinusoidal in time, and in the axial and azimuthal directions; the convected wave equation leads to a radial dependence specified by an ordinary second-order differential equation, with two singularities, at the origin and at infinity. Both singularities are irregular, implying that the acoustic fields have an essential singularity. In the neighborhood of the vortex axis, the essential singularity of the acoustic field is specified by an exponential of the integrated Doppler shift; using the latter as a factor, the acoustic fields are specified by asymptotic expansions in ascending powers of the radius. In the neighborhood of the point at infinity, where the tangential mean flow velocity vanishes, the leading terms are outward or inward propagating cylindrical waves; these factors multiply asymptotic expansions in descending powers of the radius. The two pairs of solutions, around the vortex axis and the point-at-infinity are valid in all space or overlapping regions, as far as the asymptotic expansions can be calculated. The case of an annular nozzle, with uniform axial flow, and potential swirl is used as an example; the eigenvalues are obtained for rigid wall boundary conditions and the corresponding eigenfunctions are plotted.

Candelier, F., Angilella, J. R. and Souhar, M.

"ON THE EFFECT OF THE BOUSSINESQ-BASSET FORCE ON THE RADIAL MIGRATION OF A STOKES PARTICLE IN A VORTEX"

Physics of Fluids, Vol. 16, No. 5, May 2004, pp. 1765-1776

The trajectory of an isolated solid particle dropped in the core of a vertical vortex is investigated theoretically and experimentally, in order to analyze the effect of the history force on the radial migration of the inclusion. Both the Stokes number (based on the particle radius and the fluid angular velocity) and the particle Reynolds number are small. The particle is heavier than the fluid, and is therefore expelled from the center of the vortex. An experimental device using spherical particles injected in a rotating cylindrical tank filled with silicone oil has been built. Experimental trajectories are compared to analytical solutions of the motion equations, which are obtained by making use of classical Laplace transforms. The analytical expression of the history force and the ejection rate are carried out. This force does not vanish, but increases exponentially and must be considered for efficient predictions. In particular, calculation without history force overestimates particle ejection. The relative difference between the ejection rate with and without history force scales like the square root of the Stokes number, so that differences of the order of 10% are visible as soon as the Stokes number is of the order of 0.01. Also, agreement between experimental and theoretical trajectories is observed only if the acceleration term in the history integral involves the time derivative of the fluid velocity following the particle, rather than the acceleration of fluid points at the particle location, even for small particle Reynolds numbers. Finally, analytical calculations show that the particle ejection rate is more sensitive to the Boussinesq-Basset force than to Saffman's lift.

Cann, S. R.

"AIRCRAFT VORTEX WAKE"

Shell Aviation News, No. 394, 1971, pp. 8-9

Consideration is given to the trailing vortices shed by the lifting surfaces of an aircraft. Vortex strength varies directly with the lift being produced by the wing and inversely as the speed and the span. Thus, it is that at low speeds - i.e., in control zones - that wake effects become important. Encounters of aircraft with wakes produced by other aircraft can result in uncontrollability. Current UK separation standards are summarized.

Canonne, E., Benoit, C. and Jeanfaivre, G.

"CYLINDRICAL MESH ADAPTATION FOR ISOLATED ROTORS IN HOVER"

Aerospace Science and Technology, Vol. 8, 2004, pp. 1-10

This paper presents inviscid computations of an isolated rotor in hover using a specific mesh adaptation technique. The proposed adaptation method is simple, efficient, and dedicated to this type of application. The user provides a short and fine grid around each blade; an overset cylindrical grid that discretizes the remaining part of the computational domain is then automatically generated and periodically adapted to improve the capture of the wake. This technique can also be applied to a portion of a multi-bladed rotor by using periodic boundary conditions. Transfers between blade and cylindrical grid are completed through the Chimera method. Results show that, with about 600,000 points, the tip vortex can be followed for approximately 380 degrees of age. Also, this paper proposes a deep insight into different refinement indicators for this problem.

CAO, Y.

"METHOD FOR PREDICTING ROTOR VORTEX WAKE AND DOWNWASH VELOCITY FIELD"

Journal of Beijing University of Aeronautics and Astronautics, Vol. 26, Issue 2, 2000, pp. 174-177.

An analytical method for predicting rotor vortex wake in low speed and hovering flight is described to investigate the motion of the helical tip vortex. Beginning with the prescribed wake model, a semi-empirical correction for the vortex core effect on rotor wake is made and free wake calculation is carried out. Then on the condition of circulation and wake geometry convergence, the rotor thrust is calculated to satisfy convergence criterion of thrust. Finally, as an example of its engineering application, the calculated downwash velocity field along the rocket launch line is presented and simply analyzed. In terms of theory, the calculating method developed here may provide referable basis for further studying the formation mode of the tip vortex and vortex core interior structure. Also the method is practical for predicting rotor induced flow field in engineering applications.

Cao, Y.

"A NEW METHOD FOR PREDICTING ROTOR WAKE GEOMETRIES AND DOWNWASH VELOCITY FIELD"

Aircraft Engineering and Aerospace Technology, Vol. 71, No. 2, 1999, pp. 129-135.

A new method for predicting rotor wake in low speed and hovering flight is described to investigate the motion of the helical tip vortex. Beginning with the generalized wake model, a semi-empirical correction for the vortex core effect on rotor wake is made and free wake calculation is carried out. As an example of its engineering application, the calculated downwash velocity field along the rocket launch line is presented and simply analyzed. In terms of theory, the method developed here may provide a referable basis for further study of the formation mode of the tip vortex and vortex core interior structure.

Cao, Y. and Su, Y.

"INSIGHT INTO THE EFFECTS OF ROTOR DOWNWASH ON ENGINE JET"

Aircraft Engineering and Aerospace Technology, Vol. 75, No. 4, 2003, pp. 345-349

An analytical method to predict the effects of rotor downwash on engine jet was proposed to investigate the flow pattern of helicopter engine jet. First, free wake analysis was carried out to calculate the rotor wake geometry and the downwash around the engine jet space. Then the engine jet path, cross section shape and physical variants were calculated and analyzed. Finally, an example was given to show the typical results for an insight into the influence of engine jet upon the temperature distribution around a helicopter. The method developed here can be used to predict rotor wake, engine jet and temperature distribution of a helicopter.

Cao, Y. and Zhao, M.

"NUMERICAL SIMULATION OF ROTOR FLOWFIELDS BASED ON SEVERAL SPATIAL DISCRETIZATION SCHEMES"

Journal of Aircraft, Vol. 49, No. 5, September-October 2012, pp. 1535-1540.

A method of unsteady rotor flow field simulation was developed. Several spatial schemes were used for comprehensive comparison, some advantages and disadvantages of which were assessed. The overset grid technique was implemented, and the grid system was proven to have the capability to establish inter-grid communication accurately. Comparisons among experimental data, previous references, and present simulation results were carried out to verify the accuracy and feasibility of the current methodology. Vorticity contours were also analyzed. With the help of a dual time-stepping method, an unsteady solution of the rotor flowfield was eventually obtained.

Cao, Y., Su, Y. and Zhang, Q.

"NUMERICAL SIMULATION OF HELICOPTER ENGINE JET AND FUSELAGE TEMPERATURE FIELD"

Journal of Aircraft, Vol. 43, No. 6, November-December 2006, pp. 1949-1953.

This paper presents a numerical simulation method to predict helicopter engine jet and fuselage temperature field. Rotor free wake analysis was first carried out to calculate rotor wake geometry and the downwash velocity field around the engine jet space. Then engine jet path, cross section shape, and physical variants were calculated and analyzed. Finally, an engineering method was given to calculate the fuselage temperature for insight into the influence of engine jet upon the temperature distribution around a helicopter. The method established here can be used to predict rotor wake, engine jet, and temperature distribution of a helicopter.

Cao, Y., Yu, Z. and Su, Y.

"A COUPLED FREE WAKE -- CFD METHOD FOR THE SIMULATION OF HELICOPTER ROTOR FLOW"

Canadian Aeronautics and Space Journal, Vol. 48, No. 4, December 2002, pp. 251-258

A new coupled wake -- CFD method is used to include realistic wake effects in CFD solutions for rotor flow in hover. The analytical method for predicting hovering rotor wake is described to investigate the motion of the helical tip vortex. Beginning with the generalized wake model, a semi-empirical correction for the vortex core effect on rotor wake is made. Then on the condition of circulation and wake geometry convergence, the free wake calculation is accomplished. Finally, Euler-Navier-Stokes equations are solved for transonic rotor flow employing Jameson's finite-volume explicit Runge-Kutta time-stepping scheme. The results are compared with the respective references and experimental data.

Cappellazzo, V., Treve, V., Chalon, C. and De Visscher, I.

"DESIGN PRINCIPLES FOR A SEPARATION SUPPORT TOOL ALLOWING OPTIMIZED RUNWAY DELIVERY"

AIAA Paper 2018-4237, June 2018, Atlanta, GA.

The research in the wake vortex domain made possible in the last years to tackle airport capacity issues by designing new concepts for wake separations between aircraft on approach and departure. These new solutions allow for dynamic wake separation reduction depending on aircraft characteristics and weather conditions. Amongst those concepts are found Time-Based Separation (TBS), RECAT Pairwise (RECAT-PWS) and Weather Dependent Separation (WDS). However, the application of dynamic separations entails the use of a spacing delivery support tool. This tool shall compute the applicable time- or distance-based separation minima and provide distance indicators supporting their correct delivery by the controller. Distance indicators have hence to account for aircraft separation compression effects but also for the uncertainties related to aircraft speed and wind evolution. This paper presents the principles used for the design of a demonstrator of such a separation delivery platform called LORD. The LORD tool makes use of a methodology to mitigate separation infringement

and to prevent aircraft under spacing by using an additional buffer on the spacing computation. The use of such buffers allows the separations to be correctly delivered up to a certain 'failure rate' equivalent to what is currently observed at airports while still providing capacity benefits with a better spacing management by the controller in different separation modes (e.g. distance based or time based). To prevent spacing infringement, different support warnings are also implemented in the tool. These warnings are to be used as safety nets to quickly identify potential issues in the approach/landing phase and allow the controller to take corrective actions. The LORD tool was successfully tested by Air Traffic Controllers during Real-Time Simulation campaigns. The use of the new separation concepts together with the LORD tool is seen to allow for an increase of throughput and reduction of separation infringement, while maintaining workload and situation awareness at an acceptable level.

Caradonna, F.

"PERFORMANCE MEASUREMENT AND WAKE CHARACTERISTICS OF A MODEL ROTOR IN AXIAL FLIGHT"

J. American Helicopter Society, Vol. 44, No. 2, April 1999, pp. 101-108

This paper studies the concept of extracting hover performance from model rotor climb data by extrapolating to the limit of zero climb speed. A 2-bladed rotor was mounted horizontally and tested in the 30' x 31' settling chamber of the Ames 7' x 10' #1 wind tunnel. Video cameras were used to visualize the flow field illuminated by pulsed white light sheets. With a steady, non-recirculating flow, the rotor wake was seen to be fully periodic, with little diffusion of the vortices for several rotor cycles. The transition to the far wake was seen to occur through a periodic pairing of the tip vortices, followed by their merging into a single diffuse vortex for each rotor cycle. The number of discrete vortices turns in the near wake before the pairing varied with the thrust coefficient and rate of climb.

Caradonna, F. X. and Tung, C.

"EXPERIMENTAL AND ANALYTICAL STUDIES OF A MODEL HELICOPTER ROTOR IN HOVER"

NASA TM-81232, September 1981, US Army Research and Technology Laboratories, Moffett Field, CA.

The present study is a benchmark test to aid the development of various rotor performance codes. The study involves simultaneous blade pressure measurements and tip vortex surveys. Measurements were made for a wide range of tip Mach numbers including the transonic flow region. The measured tip vortex strength and geometry permit effective blade loading predictions when used as input to a prescribed wake lifting surface code. It is also shown that with proper inflow and boundary layer modeling, the supercritical flow regime may be accurately predicted.

Caradonna, F. X., Ortega, J., Savas, O. and Dietz, W.

"ADVANCES IN ROTORCRAFT WAKE AERODYNAMICS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001.

Subsonic aerodynamics encompasses a wide array of problems. Of these, it may be that rotorcraft aerodynamics is the most varied and complex, a major cause for difficulty being the dominance of wake flows. While such flows have been the subject of both experimental and computational studies for many years, the field of study is far from being exhausted. Indeed, the need and opportunity for new studies and new ideas seems to be as great as ever. This presentation is intended to illustrate this point with a number of computational and experimental developments under recent or current development at or with the U.S. Army Aeroflightdynamics Directorate (AFDD). Wakes have probably constituted the largest single area of experimental rotor study over the years. And yet new phenomena are always being discovered. For instance, a vortex-pairing phenomenon was discovered by several different researchers recently using stroboscopic smoke flow visualization and shadowgraph. Particle Image Velocimetry (PIV) has been shown to be particularly useful in a water facility. The small rotor scale combined with the use of PIV permits a visualization and measurement of an entire rotor wake flow, clearly showing the convection and dissipation of the starting vortex, blade tip vortices and shed vorticity sheets. The prediction of such wake flows using CFD is a very difficult matter because of the grid sizes that are required to avoid numerical dissipation. Two new efficient schemes, designed to counteract the effects of this dissipation, will be described. The first, an Eulerian-Lagrangian scheme, called 'vortex embedding', is a potential-based method wherein vortex particles undergo Lagrangian convection with the induced flow predicted by a solution of the Potential equation. Because there is no vorticity dissipation here, the method requires only a coarse grid. Another method, that is more general, is the method of 'vorticity confinement'. This approach applies an artificial antidiffusive correction term that assures the non-spreading of thin vortical regions. Because diffusive spreading does not occur with this method, relatively coarse grids again can be used and the method is highly versatile.

Caram, J. M. and Ahmed, A.

"DEVELOPMENT OF THE WAKE OF AN AIRFOIL WITH RIBLETS"

AIAA Journal, Vol. 30, No. 12, December 1992, pp. 2817-2818

Tests were conducted on a NACA 0012 airfoil with riblets at a freestream Reynolds number of 2.5×10^5 in the Texas A&M University indraft wind tunnel. The riblets used in the investigation were of symmetric v-groove type with the heights of 0.0229, 0.076, and 0.152 mm. Measurements of the mean velocity profiles, turbulence, and integral quantities in the near and intermediate wakes indicated that the growth of the wake of an airfoil with riblets was like that of a clean airfoil. It was also observed that even at a distance of 600 momentum thicknesses downstream of the trailing edge wake equilibrium had not been reached for any of the configurations tested; however, riblet effectiveness was indicated by a marked decrease in the level of maximum shear stress, especially for the 0.152 mm riblets.

Caram, J. M. and Ahmed, A.

"EFFECTS OF RIBLETS ON THE WAKE CHARACTERISTICS OF AN AIRFOIL"

AIAA Paper No. 1989-2199, Seattle, WA, August 1989

Near- and intermediate-wake region boundary layer profile and skin friction coefficient measurements have been conducted for a NACA 0012 airfoil incorporating 0.0229, 0.076, and 0.152 mm symmetric v-groove riblets at a freestream Reynolds number of 250,000. While the growth of the wake was found to be similar for both the clean and the riblet-surfaces airfoils, riblet effectiveness in drag reduction was indicated by a significant decrease in wake turbulence levels. A drag reduction of as much as 13.3 percent was achieved, perhaps due to a combination of skin friction diminution in the riblet valleys and a decrease in turbulent shear stress.

Carbaugh, D. C. and Forsythe, W. D.

"WAKE TURBULENCE TRAINING AND REGULATION: AN INDUSTRY TEAM APPROACH"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 12-1 to 12-6

This paper describes the development and content of the industry endorsed Wake Turbulence Training Aid and Industry's input to regulators regarding wake turbulence efforts. The Wake Turbulence Training Aid is a safety document aimed at both pilots and air traffic controllers. The aid consists of a manual with pull out sections for easy use and a video of about 25 minutes in length. The reason for developing the aid is discussed. Increased traffic, mixed traffic, accidents and incidents, ASRS reports, and calls for action all culminated in needing training to step up to the need for more awareness and education for pilots and controllers. Who was involved in the development of the aid is discussed to highlight its international scope, as well as the time progression towards completion. The content of the aid is then discussed in detail. Lastly the efforts of the industry team to make specific inputs to the FAA regarding efforts to reduce wake turbulence encounters and to improve safety is presented.

Carey, A. W., Darmofal, D. L. and Powell, K. G.

"ONSET OF THE SPIRAL MODE OF VORTEX BREAKDOWN"

AIAA Paper No. 1997-0439, Reno, NV, January 1997

The three-dimensional nature of vortex breakdown, while widely recognized, has seldom been included in the analytical investigations and, until recently, the numerical simulations of this phenomenon. The principle asymmetric effects are examined by considering the impact that a weak perturbation has on an axisymmetric vortex. It is demonstrated that large axisymmetric strain rates are required for a non-axisymmetric perturbation to grow. Simulations bear out this fact by showing significant asymmetric behavior only after a critical swirl is exceeded which leads to breakdown in an axisymmetric flow. This result supports previous investigations which predict breakdown for an axisymmetric flow, despite their inability to fully capture the complexity of the breakdown topology.

Furthermore, this finding indicates that vortex breakdown may be a predominantly axisymmetric occurrence which is complicated by three-dimensional effects.

Caridi, G. C. A., Sciacchitano, A. and Scarano, F.

"HELIUM-FILLED SOAP BUBBLES FOR VORTEX CORE VELOCIMETRY"

Experiments in Fluids, Vol. 58, 2017, pp. 130-1 to 130-12.

Velocity measurements within the core of high-swirl vortices are often hampered by heavier-than-air particle tracers being centrifuged outside the vortex core region. The use of neutrally buoyant and lighter-than-air tracers is investigated to aim at homogeneous tracers' concentration in air flow experiments dealing with high-swirl vortices using particle image velocimetry. Helium-filled soap bubbles (HFSB) of sub-millimeter diameter are employed as flow tracers. Their density is controlled varying the relative amount of helium and soap solution composing the bubbles. The dynamics of HFSB and micro-size droplets is modeled within a Lamb-Oseen vortex to retrieve the order of magnitude of the tracers slip velocity. A positive radial drift for heavier-than-air tracers leads to an empty vortex core. In contrast, the concentration at the vortex axis is expected to increase for lighter than air tracers. Experiments are conducted on a sharp-edged slender delta wing at 20 degrees incidence. At chosen chord-based Reynolds numbers of 200,000 and 600,000, a stable laminar vortex is formed above the delta wing. Laser sheet visualization is used to inspect the spatial concentration of tracers. A comparison is made between micron-sized fog droplets and HFSB tracers in the nearly neutrally buoyant condition. Stereo-PIV measurements with fog droplets return a systematically underestimated axial velocity distribution within the vortex core due to drop-out of image cross-correlation signal. The nearly neutrally buoyant HFSB tracers appear to maintain a homogeneous spatial concentration and yield cross-correlation signal up to the vortex axis. The resulting velocity measurements are in good agreement with literature data.

Carion, J.-P., Thobois, L., Parmentier, R., Boquet, M. and Loaec, S.

"ASSESSING THE METROLOGICAL CAPABILITIES OF WIND DOPPLER LIDARS"

17th Coherent Lidar Conference, June 2013, Barcelona, Spain.

Since lidars are becoming industrial instruments, it is mandatory to ensure a good traceability of parameters and performances for all users. For most Doppler lidar applications, an accurate metrology is required, first of course for the radial wind component, but also for range and line of sight direction. To give to the user the more reliable information about its products, Leosphere is conducting a metrology plan, based on theoretical assumptions, simulation computations and experimental validations.

Cariou, J.-P. and Ludovic, T.

"COLLECTING LARGE WAKE VORTEX DATA WITH OPERATIONAL DOPPLER LIDARS FOR OPERATIONAL IMPLEMENTING OF NEW WAKE TURBULENCE REGULATIONS AT MAJOR AIRPORTS"

19th Coherent Laser Radar Conference (CLRC), Paper Th4, June 2018, Okinawa, Japan.

For twenty years, coherent Doppler LIDAR systems (CDL) have been used for better understanding wake vortices (WV) behaviors at airports. All these studies helped to design new concepts of wake separations like the RECAT regulation consisting in redefining new WT categories. These new regulations are now under investigation by many airports worldwide in order to validate their operational implementation. A review of the different technologies of CDLs used for wake vortex measurements is performed, as well as a review of the different types of wake vortex (WV) algorithm. The presentation describes in more detail one robust, automatic and accurate algorithm based on radial wind speeds designed for collecting large WV data for operational projects. It shows several examples of operational projects at major airports in the world like Paris-Charles de Gaulle airport or Hong Kong airport where wake vortex data collection has been started with CDLs.

Cariou, J.-P., Ludovic, T. and Sebastien, C.

"END-TO-END SIMULATION OF A COHERENT LIDAR IN A TURBULENT WIND FIELD"

19th Coherent Laser Radar Conference (CLRC), Paper P26, June 2018, Okinawa, Japan.

For operational applications such as wind resource assessment or turbine control, to warranty the performances in velocity accuracy and data availability is required. A Lidar simulator (Simulid TM) has been developed for assessing the velocity accuracy and the data availability of pulsed coherent wind Doppler Lidar system worldwide. This simulator considers both the Lidar parameters (instrument hardware, signal processing, beam propagation...) and the aerosol properties. Recently, Simulid TM has been coupled with a 3D wind model (Turbsim) to perform simulated wind measurements in any representative wind field, including turbulence. We present the methodology and the validation process. Velocity accuracy is compared with experimental tests performed in a frozen propagation medium and the representativeness of the simulated wind measurements is discussed.

Cariou, J.-P., Ludovic, T. and Spencer, P.

"FROM WINDCUBE#0001 TO WINDCUBE#1000: DOPPLER LIDAR AS A MATURE TECHNOLOGY"

19th Coherent Laser Radar Conference (CLRC), Paper Th14, June 2018, Okinawa, Japan.

10 years after the Windcube #0001, Leosphere has delivered its 1000th Windcube Doppler Lidar. Still based on pulsed fibered technology at 1.5 microns, the Windcube is now an industrial product widely used for Wind Resource Assessment and Weather Monitoring. Tracing the path of technological progress from laboratory to industry in hardware and software, but also the progress in metrology, the presentation expresses the various and demanding application requirements, the continuous

improvements of coherent lidar solutions and the slow but inexorable acceptance of remote sensors in wind energy and meteorological applications.

Cariou, J.-P., Pureur, V. and Hwryniack, E.

"ALL SEMICONDUCTOR PULSED DOPPLER LIDAR FOR WIND SENSING"

19th Coherent Laser Radar Conference (CLRC), Paper P18, June 2018, Okinawa, Japan.

Coherent Doppler lidars are usually powered by optical fiber amplifiers or solid-state bulk amplifiers. Thanks to recent improvements of semiconductor optical amplifiers (SOA), we have demonstrated the first 1.5 micron all semiconductor pulsed Doppler lidar for wind sensing. Low pulse energy typically available in SOAs is balanced by high pulse repetition frequency, allowing range resolved measurement of wind from 40 m to about 200 m with 20 m range resolution. While amplifying, the SOA shapes the light pulse leading to a quite simple, compact, and cost-effective setup. First results are shown and early atmospheric wind measurements are compared with a reference Windcube fibered lidar.

Cariou, J.-P., Thobois, L., Germon, Q., Dolfi-Bouteyre, A. and Durecu, A.

"DEVELOPMENT OF A HIGH-POWER DOPPLER WIND LIDAR FOR MEASURING WIND AND EDR ALONG AIRCRAFT APPROACHES"

18th Coherent Laser Radar Conference, June 2016, Boulder, CO.

Air flows in the troposphere have a major impact on air traffic safety and operations. In the framework of the European UFO project, LEOSPHERE and ONERA have developed a new high powered scanning Doppler LIDAR using an innovative powerful Erbium doped fiber laser amplifier. The performances of this prototype have been evaluated through a campaign in 2014 performed at Toulouse airport, France. In addition, specific algorithms have been developed for retrieving wind and EDR quantities along aircraft approaches and in 3D around airport. The wind and EDR measurements have been then compared to reference sensors in order to assess their accuracy.

Carley, M.

"A TRIANGULATED VORTEX METHOD FOR THE AXISYMMETRIC EULER EQUATIONS"

Journal of Computational Physics, Vol. 180, 2002, pp. 616-641

A new method is presented for the prediction of unsteady axisymmetric inviscid flows. By combining a triangulated vortex approach with a novel evaluation technique for the Biot-Savart integrals, a Lagrangian vortex method is developed which eliminates the singularities usually present in axisymmetric methods, without recourse to normalization or other approximations. Furthermore, the computational effort scales as the number of control points N and, in the large N limit, depends only on the order of quadrature employed. The accuracy and computational effort are assessed by comparison

with the velocity field of a Gaussian core vortex ring and the use of the technique is illustrated by computation of the motion of Norbury rings and of vortex ring pairing.

Carlisle, D.

"AIRCRAFT WAKE TURBULENCE"

Business and Commercial Aviation, Vol. 85, No. 5, November 1999, pp. 72-78

Understanding the physical characteristics of wake turbulence vortices and the hazard they represent is the key to developing effective strategies for avoiding wake turbulence encounters.

Carmer, C. F. v., Heider, A., Schroder, A., Konrath, R., Agocs, J., Gilliot, A. and Monnier, J.-C.

"EVALUATION OF LARGE-SCALE WING VORTEX WAKES FROM MULTI-CAMERA PIV MEASUREMENTS IN FREE-FLIGHT LABORATORY,:"

Topics in Applied Physics, Vol. 112, 2008, pp. 377-39.

Multiple-vortex systems of aircraft wakes have been investigated experimentally in a unique large-scale laboratory facility, the free-flight B20 catapult bench, ONERA Lille. 2D/2C PIV measurements have been performed in a translating reference frame, which provided time-resolved cross-velocity observations of the vortex systems in a Lagrangian frame normal to the wake axis. A PIV setup using a moving multiple-camera array and a variable double-frame time delay has been employed successfully. The large-scale quasi-2D structures of the wake-vortex system have been identified and illustrate the temporal development of unequal-strength corotating vortex pairs in aircraft wakes for nondimensional times up to 45.

Carmer, C. F. v., Konrath, R., Schroder, A. and Monnier, J.-C.

"IDENTIFICATION OF VORTEX PAIRS IN AIRCRAFT WAKES FROM SECTIONAL VELOCITY DATA"

Exp Fluids, Vol. 44, 2008, pp. 367-380

The dynamics of multiple-vortex wake systems behind aircraft endangering air traffic can be assessed also from physical modelling. Large-scale laboratory investigations of multiple-vortex systems have been performed in a free-flight laboratory and in a water towing tank. Specialized PIV measurements provide time-resolved flow velocity fields normal to the wake axis. The applicability of various velocity-gradient tensor-based vortex identification schemes to planar velocity data is addressed and demonstrated for unequal-strength co- and counter-rotating vortex pairs. Large vortices shed off the wing tips and flaps are identified employing a velocity-gradient tensor criterion. Their cooperative mechanisms of generation and decay are evidenced from iso-surfaces of squared swirling strength and from further characteristic vortex parameters.

Carnevale, G. F., Kloosterziel, R. C., Orlandi, P. and van Sommeren, D. D. J. A.

"PREDICTING THE AFTERMATH OF VORTEX BREAKUP IN ROTATING FLOW"

Journal of Fluid Mechanics, Vol. 669, 2011, pp. 90-119.

A method for predicting the outcome of vortex breakup in a rotating flow is introduced. The vortices dealt with here are subject to both centrifugal and barotropic instabilities. The prediction of the aftermath of the breakup relies on knowing how both centrifugal and barotropic instabilities would equilibrate separately. A theoretical model for non-linear equilibration in centrifugal instability is wedded to two-dimensional simulation of barotropic instability to predict the final vortices that emerge from the debris of the original vortex. This prediction method is tested against three-dimensional Navier-Stokes simulations. For vortices in which a rapid centrifugal instability triggers a slower barotropic instability, the method is successful both qualitatively and quantitatively. The skill of the prediction method decreases as the time scales of the two instabilities become comparable.

Carpenter, A. G.

"SUMMARY AND EVALUATION OF THEORETICAL DEVELOPMENTS RELATING TO TRAILING WING TIP VORTICES GENERATED BY AIRCRAFT"

SAC-NR-76-01, May 1976, Strategic Air Command, Offutt AFB, NB

This report presents a summary of theories and measurements which are believed to be applicable to the prediction of details concerning the structure and behavior of wing tip vortices created by large aircraft. Emphasis is placed upon the chronological development of theories, their comparison, and the selection of those which are believed to be most useful in predicting detailed velocity profiles of and within vortices from the moment of wing tip shedding until considerable trailing distances have been established with the passage of time.

Carr, J. W.

"SURFACE VELOCITIES AND TEMPERATURE CHANGES FOR C-130, C-141, AND C-5A EXHAUST BLASTS AND C-5A WING-TIP VORTEX"

AEWES-S-73-61, June 1973, Army Engineer Waterways Experiment Station, Vicksburg, M.

The report describes a series of field investigations conducted to determine exhaust-blast velocities and temperatures at the ground level for various aircraft and the wing-tip vortex velocity of the C-5A. Measurements of exhaust-blast velocities and temperature rise during static conditions were collected for C-130, C-141, and C-5A aircraft. Taxi, breakaway, and liftoff tests were conducted with the C-141 and C-5A to record velocity during actual aircraft operations. Wind velocity created by the wing-tip vortex of the C-5A was recorded during actual aircraft operations. Results of these tests indicate that temperature increases from engine exhaust blasts are not sufficient to cause detrimental effects on runway surfacing in use to date.

Carr, Z., Chen, C. and Ringuelette, M. J.

"THE EFFECT OF ASPECT RATIO ON THE THREE-DIMENSIONAL VORTEX FORMATION OF ROTATING FLAT-PLATE WINGS"

AIAA Paper No. 2012-0912, January 2012, Nashville, Tennessee.

We investigate experimentally the effect of aspect ratio (AR) on the unsteady, three-dimensional vortex structure of low-AR, flat-plate wings rotating from rest with a 45-degree angle of attack. This configuration is a simplified model of a flapping-wing hovering half-stroke. The objectives are to quantitatively characterize the evolution of the detailed, three-dimensional vortex structure and its variation with AR. The experiments are conducted in a glass tank facility containing a mixture of glycerin and water. Plates of AR=2 and 4 are tested, using a trapezoidal velocity program with a tip Reynolds number of 5,000 for each and a total rotation of 120 degrees. The unsteady, three-dimensional, volumetric velocity data are reconstructed from phase-locked and phase-averaged stereoscopic digital particle image velocimetry measurements in multiple, closely-spaced chordwise planes. The three-dimensional vortex formation is characterized using the Q-criterion and the helicity density. For each AR we find that the overall vortex structure is a loop consisting of a connection among the leading-edge, tip, and trailing edge vortices. For both AR's the leading-edge vortex (LEV) is larger with increasing span, i.e. conical, which is more pronounced for AR=4. The LEV for each AR is attached over the inboard portion of the plate up to about 50 percent span throughout the motion. However, after approximately 30 degrees of rotation it detaches from the plate in the outboard region near the tip, forming an arch-like structure. The arch is anchored at the tip due to the influence of the tip vortex. A second LEV then forms in front of the arch and does not exhibit shedding into the wake. In contrast, for AR=4 the flow structure in the tip region breaks down significantly and the flow appears to be fully separated for the remainder of the run. A Kelvin-Helmholtz instability is observed in the separated shear layers at the tip and trailing edges for both AR's.

Carrion, M., Woodgate, M., Steijl, R., Barakos, G. N., Gomez-Iradi, S. and Munduate, X.

"UNDERSTANDING WIND-TURBINE WAKE BREAKDOWN USING COMPUTATIONAL FLUID DYNAMICS"

AIAA Journal, Vol. 53, No. 3, March 2015, pp. 588-602.

This work explores the breakdown of the wake downstream of the Model Experiments in Controlled Conditions Project (known as the MEXICO project) wind-turbine rotor and assesses the capability of computational fluid dynamics in predicting its correct physical mechanism. The wake is resolved on a fine mesh able to capture the vortices up to eight rotor radii downstream of the blades. At a wind speed of 15 m/s, the main frequency present in the computational fluid dynamics signals for up to four radii was the blade-passing frequency (21.4 Hz), where the vortex cores fall on a perfect spiral. Between four and five radii downstream, higher-frequency content was present, which indicated the onset of instabilities and results in vortex pairing. The effect of modeling a 120 deg azimuthally periodic domain and a 360 deg three-bladed rotor domain was studied, showing similar predictions for the location of the onset of instabilities. An increased frequency content was captured in the latter

case. Empirical and wake models were also explored, they were compared with computational fluid dynamics, and a combination of kinematic and field models was proposed. The obtained results are encouraging and suggest that the wake instability of wind turbines can be predicted with computational fluid dynamics methods, provided adequate mesh resolution is used.

Carten, Jr., A. S.

"AIRCRAFT WAKE TURBULENCE - AN INTERESTING PHENOMENON TURNED KILLER"

Air University Review, Vol. XXII, No. 5, July/August 1971, pp. 12-24

The Aircraft Wake Turbulence problem is described in operational terms and is compared with another environmentally oriented problem: Clear Air Turbulence. The history of the investigation of wing tip vortices is traced from the earliest days of manned flight to the present time of crisis. A simplified theoretical explanation (based on the work of Spreiter and Sacks) is given for the phenomenon. Various possible methods of alleviation and problem control are described along with current on-going research efforts by various concerned groups.

Carten, Jr., A. S.

"THE AIRCRAFT WAKE TURBULENCE PROBLEM"

AIAA Student Journal, Vol. 10, No. 4, December 1972, pp. 8-13

This paper reports on the potential hazard resulting from the wake vortices generated by the heavy aircraft. An account is given of the conventional theory used to describe the vortex.

Carten, Jr., A. S.

"WARNING: WAKES"

Astronautics and Aeronautics, Vol. 8, No. 4, April 1970, pp. 76-81

This paper is written from the point of view of the airfield meteorological equipment designer. It considers the new problems associated with the just-introduced wide-body jet aircraft and assesses their probable impact on airfield meteorological equipment performance and siting requirements. Jet exhaust wakes caused by taxiing and takeoff operations are treated in detail. Wing tip vortex characteristics are discussed, citing the findings of other authors.

Carton, X., Maze, G, and Legras, B.

"A TWO-DIMENSIONAL VORTEX MERGER IN AN EXTERNAL STRAIN FIELD"

Journal of Turbulence, Vol. 3, Paper 045, October 2002, pp. 1-7

In a two-dimensional incompressible fluid, the merger of two Rankine vortices in an external strain field is studied analytically and numerically. In the absence of merger, the trajectory of the vortex centers is elliptical near the center of the plane and hyperbolic at larger distances. When merger occurs, it can be accelerated or decelerated by the external strain field depending on the orientation of the strain axes, but in all the cases studied here, external strain decreases merger efficiency.

Cary, A. W., Darmofal, D. L. and Powell K. G.

"ONSET OF THE SPIRAL MODE OF VORTEX BREAKDOWN"

AIAA Paper No. 1997-0439, Reno, NV, January 1997

The three-dimensional nature of vortex breakdown, while widely recognized, has seldom been included in the analytical investigations and, until recently, the numerical simulations of this phenomenon. The principle asymmetric effects are examined by considering the impact that a weak perturbation has on an axisymmetric vortex. It is demonstrated that large axisymmetric strain rates are required for a non-axisymmetric perturbation to grow. Simulations bear out this fact by showing significant asymmetric behavior only after a critical swirl is exceeded which leads to breakdown in an axisymmetric flow. This result supports previous investigations which predict breakdown for an axisymmetric flow despite their inability to fully capture the complexity of the breakdown topology. Furthermore, this finding indicates that vortex breakdown may be a predominantly axisymmetric occurrence which is complicated by three-dimensional effects.

Casalino, D., Hazir, A., Fares, E., Duda, B. and Khorrami, M. R.

"ON THE CONNECTION BETWEEN FLAP SIDE-EDGE NOISE AND TIP VORTEX DYNAMICS"

AIAA Paper 2015-2992, June 2015, Dallas, TX.

The goal of the present work is to investigate how the dynamics of the vortical flow about the flap side edge of an aircraft determine the acoustic radiation. A validated lattice-Boltzmann CFD solution of the unsteady flow about a detailed business jet configuration in approach conditions is used for the present analysis. Evidence of the connection between the noise generated by several segments of the inboard flap tip and the aerodynamic forces acting on the same segments is given, proving that the noise generation mechanism has a spatially coherent and acoustically compact character on the scale of the flap chord, and that the edge-scattering effects are of secondary importance. Subsequently, evidence of the connection between the kinematics of the tip vortex system and the aerodynamic force is provided. The kinematics of the dual vortex system are investigated via a core detection technique. Emphasis is placed on the mutual induction effects between the two main vortices rolling up from the pressure and suction sides of the flap edge. A simple heuristic formula that relates the far-field noise spectrum and the cross-spectrum of the unsteady vortical positions is developed.

Casciola, C. M. and Piva, R.

"A LAGRANGIAN APPROACH FOR VORTICITY INTENSIFICATION IN SWIRLING RINGS"

Computational Mechanics, Vol. 21, 1998, pp. 276-282

The Lagrangian approach, adopted in vortex methods for incompressible Euler flows, is reconsidered here as the most appropriate technique to track the dynamical evolution of organized vorticity structures in free space. We analyze in this paper a specific initial condition, the swirling ring with azimuthal perturbations, from which originate vortex dynamics events leading to a localized but strong vorticity intensification. The aim is to understand the possible development of a finite time singularity, in the context of inviscid flows, and its relevance for the study of intermittency, as one of the most challenging aspects of turbulence.

Cass, S. D., Scoggins, J. R. and Chevalier, H. L.

"LOW-ALTITUDE ATMOSPHERIC TURBULENCE AROUND AN AIRPORT"

Journal of Aircraft, Vol. 10, No. 3, March 1973, pp. 157-163.

A small airplane was used to measure vertical accelerations due to atmospheric turbulence around an airport surrounded by large buildings, trees, and other objects. The vertical and lateral extent and the intensity of turbulence in the wake of buildings and at other locations around the airport were measured. Results are presented which indicate that the vertical accelerations of the airplane are related to gust intensities measured by conventional anemometers, and that reasonable forecasts of atmospheric turbulence which an airplane could expect to encounter near an airport surrounded by buildings, etc. may be made from wind data appropriately measured and analyzed.

Cassel, K. W. and Conlisk, A. T.

"UNSTEADY SEPARATION IN VORTEX-INDUCED BOUNDARY LAYERS"

Philosophical Transactions, Vol. 372, Issue 2020, July 2014, Article 20130348.

This paper provides a brief review of the analytical and numerical developments related to unsteady boundary-layer separation, in particular as it relates to vortex-induced flows, leading up to our present understanding of this important feature in high-Reynolds-number, surface-bounded flows in the presence of an adverse pressure gradient. In large part, vortex-induced separation has been the catalyst for pulling together the theory, numerics, and applications of unsteady separation. Particular attention is given to the role that Prof. Frank T. Smith, FRS, has played in these developments over the course of the past 35 years. The following points will be emphasized: (i) unsteady separation plays a pivotal role in a wide variety of high-Reynolds-number flows, (ii) asymptotic methods have been instrumental in elucidating the physics of both steady and unsteady separation, (iii) Frank T. Smith has served as a catalyst in the application of asymptotic methods to high-Reynolds-number flows, and (iv) there is still much work to do in articulating a complete theoretical understanding of unsteady boundary-layer separation.

Cassidy, J. J. and Falvey, H. T.

"OBSERVATIONS OF UNSTEADY FLOW ARISING AFTER VORTEX BREAKDOWN"

J. Fluid Mech., Vol. 41, Part 4, 1970, pp. 727-736.

In rotating flow moving axially through a straight tube, a helical vortex will be generated if the angular momentum flux is sufficiently large relative to the flux of linear momentum. This paper describes an experimental study of the occurrence, frequency and peak-to-peak amplitude of the wall pressure generated by this vortex. The experimental results are displayed in dimensionless form in terms of a Reynolds number, a momentum parameter and tube geometry.

Castro, F., Crespo, A., Manuel, F. and Fruman, D. H.

"EQUILIBRIUM OF VENTILATED CAVITIES IN TIP VORTICES"

Journal of Fluids Engineering, Vol. 119, Dec. 1997, pp. 759-767.

The behavior of air cavities formed in the tip vortex trailing from rectangular and elliptical planform hydrofoils has been examined both theoretically and experimentally. These cavities have some peculiarities, in particular their ability to move upstream and reach a stable position near the hydrofoil. Detailed measurements of the velocity components and the cavity characteristics have been made. The results are compared with the predictions of a theoretical model based on the equilibrium balance of a cavity developing in a Lamb vortex.

Catalano, F. M. and Ceron-Munoz, H. D.

"EXPERIMENTAL ANALYSIS OF AERODYNAMICS CHARACTERISTICS OF ADAPTIVE MULTI-WINGLETS"

AIAA Paper No. 2005-1231, Reno, NV, January 2005

The research aim is the study of the potential use of adaptive multi-winglets to get reductions in the induced drag through variations of cant and incidence angle of the winglets. Different studies have been showing that the flow at the wing tip can be redirect using small aerodynamics superficies, thus reducing the induced drag. The model tested was composed of a rectangular wing built from an airfoil NACA 65-018 constituted of three winglets called tip-sails, which are small wings without sweep at 25% chord. The tests were conducted at a Reynolds number of 650,000. The results are analyzed by the interpretation of lift; drag and mapping of the wake through hot-wire anemometry. Results showed that it is possible to find the best configuration of the three wing-lets in order to get the optimum aerodynamic performance for each flow regime from climb to cruise.

Cattafesta, III, L. N. and Settles, G. S.

"EXPERIMENTS ON SHOCK/VORTEX INTERACTION"

AIAA Paper No. 92-0315, Reno, NV, January 1992

The interaction between a shock wave and a supersonic streamwise vortex is a fundamental fluid dynamics problem with numerous practical applications. However, very little research has been conducted on this topic. This paper describes an experimental study of this phenomenon. In particular, supersonic streamwise vortices of varying strength and Mach number were generated and measured using five-hole and total temperature probes. In addition, the interaction between a vortex and either an oblique or a normal shock wave were visualized using schlieren and Planar Laser Scattering (PLS) techniques. The mean-flow measurements show both similarities and differences between the supersonic streamwise vortex and its incompressible counterpart, while the flow visualization results show that the shock/vortex interaction is always unsteady and that, under certain conditions, the vortex can burst. The conditions necessary for supersonic vortex breakdown are presented.

Cazalbou, J.-B., Chassaing, P., Dufour, G. and Carbonneau, X.

"TWO-EQUATION MODELING OF TURBULENT ROTATING FLOWS"

Physics of Fluids, Vol. 17, No. 5, May 2005, pp. 005110-1-0555110-14

The possibility to take into account the effects of the Coriolis acceleration on turbulence is examined in the framework of two-equation eddy-viscosity models. General results on the physical consistency of such turbulence models are derived from a dynamical-system approach to situations of time-evolving homogeneous turbulence in a rotating frame. Application of this analysis to a model fitted with an existing Coriolis correction [J. H. G. Howard, S. V. Patankar, and R. M. Bordyniuk, 'Flow prediction in rotating ducts using Coriolis-modified turbulence models' ASME Trans. J. Fluids Eng. 102, 456 (1980)] is performed. Full analytical solutions are given for the flow predicted with this model in the situation of homogeneously sheared turbulence subject to rotation. The existence of an unphysical phenomenon of blowup at finite time is demonstrated in some range of the rotation-to-shear ratio. A direct connection is made between the slope of the mean velocity profile in the plane-channel flow with spanwise rotation, and a particular fixed point of the dynamical system in homogeneously sheared turbulence subject to rotation. The general analysis, and the understanding of typical inaccuracies and misbehavior observed with the existing model, are then used to design a new model which is free from the phenomenon of blowup at finite time and able to account for both main influences of rotation on turbulence: the inhibition of the spectral transfer to high wave numbers and the shear/Coriolis instability.

Celikkol, B., Swift, M. and Yildiz, M.

"SCATTERING OF SOUND WAVES BY A TURBULENT WAKE"

Journal of Sound and Vibration., Vol. 35, No. 2, 1994, pp. 231-252

In this investigation, the Doppler shifted power spectrum of the scattering cross-section is obtained for plane acoustic waves scattered by fluid flow fluctuations appropriate to a turbulent wake. The wake considered in this paper is assumed almost homogeneous and isotropic and of low Reynolds number. It is shown that the evaluation of the Doppler scattering cross-section essentially reduces to the calculation of the wave number converted and frequency shifted energy spectrum function of the turbulent flow fluctuations. In prescribing the low Reynolds number turbulence spectrum, inertial forces are assumed negligible. Convective effects of the macro-eddies, which cause a Doppler shift in the scattered waves, are considered using a Lagrangian-type of space-time velocity correlation. After finding the spectrum of turbulent fluctuations, the Doppler shifted power spectrum of the scattering cross-section, which characterizes the scattered waves, is obtained explicitly for the far field approximation.

Centolanzi, F. J.

"MEASURED AND THEORETICAL FLOW FIELDS BEHIND A RECTANGULAR AND A TRIANGULAR WING UP TO HIGH ANGLES OF ATTACK AT A MACH NUMBER OF 2.46"

NASA TN-D-92, Sept. 1959, Ames Research Center, Moffett Field, CA.

Measurements were made of the flow field behind a rectangular and a triangular wing of aspect ratio 2 up to angles of attack of 30 degrees. The wings had a 4-inch semispan and were 5 percent thick with maximum thickness at midchord. Tests were performed at a Mach number of 2.46 and a Reynolds number of 3.12 million per foot. Flow-field measurements were taken for wing angles of attack of 0, 6, 20 and 30 degrees. The downwash, sidewash, Mach number, and dynamic pressure in the wakes of both wings are compared with the predictions of various theoretical methods. The results show that for angles of attack up to 20 degrees these flow quantities can be calculated with sufficient accuracy for most engineering purposes. The measured downwash, dynamic pressure, and Mach number in the wake of the rectangular wing were used to estimate the effectiveness of a hypothetical tail placed at various heights above and below the chord plane of the wing. The effectiveness was also computed using shock-expansion theory to determine the required flow quantities. These two calculations of the tail effectiveness are in fair agreement.

Ceron-Munoz, H. D., Cosin, R., Coimbra, R. F. F., Correa, L. G. N. and Catalano, F. M.

"EXPERIMENTAL INVESTIGATION OF WING-TIP DEVICES ON THE REDUCTION OF INDUCED DRAG"

Journal of Aircraft, Vol. 50, No. 2, March-April 2013, pp. 441-449.

Wind tunnel testing was carried out to evaluate the reduction of induced drag using wing-tip blowing, fixed and adaptive multi-winglets. Different arrangements of each device were tested on a semi-span wing, with additional investigation performed on a half-body model of a trainer aircraft. Results include: aerodynamic coefficients; surface pressure distributions; and wake surveys with a multi-hole Pitot probe. The influence of each wing-tip arrangement on aircraft performance was estimated,

considering the energy requirements of the blowing system. All devices tested were able to minimize induced drag; however, for practical applications in commercial airplanes, multi-winglets are a more promising alternative due to the large amount of energy required by wing-tip blowing.

Cerretelli, C. and Williamson, C. H. K.

"A NEW FAMILY OF UNIFORM VORTICES RELATED TO VORTEX CONFIGURATIONS BEFORE MERGING"

J. Fluid Mech., Vol. 493, 2003, pp. 219-229

Stimulated by experimental observations of vortex merging, we compute a new family of uniform-vorticity steady solutions of the Euler equations in two dimensions. In experiments with two co-rotating vortices, one finds that, prior to the convective merging phase, and the formation of vortex filaments, the initial pair diffuses into a single structure (with two vorticity peaks) in the form of a symmetric 'dumb-bell'. In the present computations, our exploration of the existence of vortex solutions has been guided by the streamline patterns of the co-rotating reference frame, and by the simple concept that the vortex boundary must be one of these streamlines. By varying the parameters which define the vortex patches, we find a family of vorticity structures which pass from the limiting case of point vortices, through the case of two equal co-rotating uniform vortices, to the regime where the vortices touch in the form of a dumb-bell. Further exploration of this family of solutions leads to an elliptic vortex, which joins precisely to the local trans-critical bifurcation from elliptic vortices with $n = 4$ perturbation symmetry that was found by Kamm (1987) and Saffman (1988). Finally, one reaches a limiting 'cat's-eye' vortex patch of two-fold symmetry ($m = 2$), which constitutes an extension to the limiting shapes of m -fold symmetry (m greater than 2) found by Wu, Overman and Zabusky (1984).

Cerretelli, C. and Williamson, C. H. K.

"THE PHYSICAL MECHANISM FOR MERGING OF TRAILING VORTICES"

J. Fluid Mech., Vol. 475, 2003, pp. 41-77

In this paper, we study the interaction of two co-rotating trailing vortices. It is well known that vortices of like-sign ultimately merge to form a single vortex, and there has been much work to measure and predict the initial conditions for the onset of merger, especially concerning the critical vortex core radius. However, the physical mechanism causing such merger has received little attention. In this work, we directly measure the structure of the antisymmetric vorticity field that causes the co-rotating vortices to be pushed towards each other during merger. We discover that the form of the antisymmetric vorticity comprises two counter-rotating vortex pairs, whose induced velocity field readily pushes the two centroids together. The merging velocity, computed from the antisymmetric vorticity field, agrees closely with such velocity measured directly from the total (original) flow field. The co-rotating vortex pair evolves through four distinct phases. The initial stage comprises a diffusive growth, which can be either viscous or turbulent. In either case, the number of turns that they rotate around one another until the vortices start to merge increases with Reynolds number (Re). If one observes the streamlines in a rotating reference frame (moving with the vortices), then one finds an

inner and outer recirculating region of the flow bounded by a separatrix streamline. When the vortices grow large enough in the first stage, diffusion across the separatrix places vorticity into the outer recirculating region of the flow, and this leads to the generation of the antisymmetric vorticity, causing convective merger. This second (convective) stage corresponds to the motion of the vortex centroids towards each other, and is a process which is almost independent of viscosity. During the late part of this stage, the antisymmetric vorticity is diminished by a symmetrization process, and the final merging into one vorticity structure is achieved by a second diffusive stage. The fourth and ultimate phase is one where the merged vortex core grows by diffusion.

Cezard, N., Besson, C., Dolfi-Bouteyre, A. and Lombard, L.

"AIRFLOW CHARACTERIZATION BY RAYLEIGH-MIE LIDARS"

Onera Journal, Issue 1, December 2009, pp. 1-4.

This paper deals with lidar systems applied to airflow measurements. The properties of the two main light scattering processes, Rayleigh and Mie scattering, are presented and correlated to general but important rules for lidar design. The Rayleigh lidar developed at Onera for short-range wind speed measurements is also presented, and the Doppler analysis technique using Michelson fringe imagery is briefly discussed.

Chaderjian, N. M.

"ADVANCES IN ROTOR PERFORMANCE AND TURBULENT WAKE SIMULATION USING DES AND ADAPTIVE MESH REFINEMENT"

Seventh International Conference on Computational Fluid Dynamics, July 2012, Big Island, Hawaii.

Time-dependent Navier-Stokes simulations have been carried out for a rigid V22 rotor in hover, and a flexible UH-60A rotor in forward flight. Emphasis is placed on understanding and characterizing the effects of high-order spatial differencing, grid resolution, and Spalart-Allmaras (SA) detached eddy simulation (DES) in predicting the rotor figure of merit (FM) and resolving the turbulent rotor wake. The FM was accurately predicted within experimental error using SA-DES. Moreover, a new adaptive mesh refinement (AMR) procedure revealed a complex and more realistic turbulent rotor wake, including the formation of turbulent structures resembling vortical worms. Time-dependent flow visualization played a crucial role in understanding the physical mechanisms involved in these complex viscous flows. The predicted vortex core growth with wake age was in good agreement with experiment. High-resolution wakes for the UH-60A in forward flight exhibited complex turbulent interactions and turbulent worms, similar to the V22. The normal force and pitching moment coefficients were in good agreement with flight-test data.

Chadwick, E.

"THE VORTEX LINE IN STEADY, INCOMPRESSIBLE OSEEN FLOW"

Proceedings of the Royal Society, Vol. A 462, Nov. 2005, pp. 391-401.

The horseshoe vortex is given in Oseen flow as a constant spanwise distribution of lift Oseenlets. From these, the vortex line is represented in steady, incompressible Oseen flow. The velocity near to the vortex line is determined, as well as near to and far from the far field wake. The velocity field in the transverse plane near to the vortex line is shown to approximate to the two-dimensional Lamb-Oseen vortex, and the velocity field in the streamwise direction is generated by the bound vortex line of the horseshoe vortex giving a streamwise decay much faster than that of the Batchelor vortex. The far field wake description is shown to be consistent with laminar wake theory.

Chadwick, E. and Rahulan, T.

"A THEORETICAL MODEL EVALUATING LEADING ORDER VORTEX DECAY BEHIND AN AIRCRAFT"

Proc. IMechE, Vol. 225, Part G, 2011, pp. 657-663.

A theoretical model in this article which is used to evaluate leading order vortex decay behind an aircraft, is presented. This model is then applied to two important problems. The first evaluates safety separation distances for the super class of aircraft exemplified by the Airbus A380. The second evaluates the swirl parameter which is shown to decay to a sufficiently low level that short-wave instabilities are likely to be instigated. The model uses the Oseen approximation, which assumes that in the far-field the ratio of the perturbed velocity to the aircraft velocity is small, and developed from recent publications by the first author. The atmospheric turbulence is incorporated into the model by using effective viscosity.

Chadwick, R. B., Jordan, J. and Detman, T.

"RADAR DETECTION OF WINGTIP VORTICES"

Proceedings 9th Conf. on Aerospace and Aeronautical Meteorology, American Meteorological Society, Omaha, NE, June 1983, pp. 235-240

It is possible to detect wingtip vortices in airport approach zones using inexpensive (<400 K) clear-air Doppler radar systems. Calibration-free techniques for determining if a vortex is in a resolution cell can probably be developed. Further work is necessary to determine if the detection capability is degraded by rain or fog. Since clear-air Doppler radars can measure hazardous wind shear, Chadwick et al. (1979), it is possible that the same radar system could be used to locate vortex hazards and detect wind shear hazards in approach zones. The operational methods for using the same radar system to solve two important problems would have to be developed, but the radar technology for detecting wind shear and wingtip vortices does exist.

Chadwick, R. B., Moran, K. P., Campbell, W. C., Earnshaw, K. B. and Detman, T. R.

"DEVELOPMENT OF A CLEAR AIR RADAR TO DETECT METEOROLOGICAL HAZARDS AT AIRPORTS"

AFGL TR-81-0268, September 1981, NOAA Wave Propagation Lab., Boulder, CO

To be useful in detecting meteorological hazards such as low-level wind shear near airports, a radar must be able to: (1) detect backscatter from both clear air and rain; (2) operate at short ranges and low elevation angles; and (3) measure Doppler frequencies caused by air motion. The development of a radar with these characteristics is described and the results of testing this radar at airports are presented. Special emphasis is placed on the problems of low elevation angle operation and clutter suppression. The importance of proper siting is pointed out. In addition, it is demonstrated that the radar can readily detect the turbulent wakes of large jet aircraft.

Chakraborty, B. B. and Chandra, J.

"RAYLEIGH-TAYLOR INSTABILITY IN THE PRESENCE OF ROTATION"

Physics of Fluids, Vol. 19, No. 12, December 1976, pp. 1851-1852

A heavy uniform fluid is superposed on a lighter one. The two uniform fluids are separated by a layer of transition of finite thickness in which the density increases exponentially in the vertical direction. The growth rate and the wavenumber of the mode of maximum instability are obtained when the whole system rotates uniformly about a vertical axis.

Chamorro, L. P. and Porte-Agel, F.

"A WIND-TUNNEL INVESTIGATION OF WIND-TURBINE WAKES: BOUNDARY-LAYER TURBULENCE EFFECTS"

Boundary-Layer Meteorology, Vol. 132, 2009, pp. 129-149.

Wind-tunnel experiments were performed to study turbulence in the wake of a model wind turbine placed in a boundary layer developed over rough and smooth surfaces. Hot-wire anemometry was used to characterize the cross-sectional distribution of mean velocity, turbulence intensity and kinematic shear stress at different locations downwind of the turbine for both surface roughness cases. Special emphasis was placed on the spatial distribution of the velocity deficit and the turbulence intensity, which are important factors affecting turbine power generation and fatigue loads in wind energy parks. Non-axisymmetric behavior of the wake is observed over both roughness types in response to the non-uniform incoming boundary-layer flow and the effect of the surface. Nonetheless, the velocity deficit with respect to the incoming velocity profile is nearly axisymmetric, except near the ground in the far wake where the wake interacts with the surface. It is found that the wind turbine induces a large enhancement of turbulence levels (positive added turbulence intensity) in the upper part of the wake. This is because of relatively large velocity fluctuations associated with helicoidal tip vortices near the wake edge, where the mean shear is strong. In the lower part of the wake, the mean shear and turbulence intensity are reduced with respect to the incoming flow. The non-axisymmetry of the turbulence intensity distribution of the wake is found to be stronger over the rough surface, where the incoming flow is less uniform at the turbine level. In the far wake the added turbulent intensity, its positive and negative contributions, and its local maximum decay as a power law of downwind distance

(with an exponent ranging from -0.3 to -0.5 for the rough surface, and with a wider variation for the smooth surface). Nevertheless, the effect of the turbine on the velocity defect and added turbulence intensity is not negligible even in the very far wake, at a distance of fifteen times the rotor diameter.

Chamorro, L. P. and Porte-Agel, F.

"EFFECTS OF THERMAL STABILITY AND INCOMING BOUNDARY-LAYER FLOW CHARACTERISTICS ON WIND-TURBINE WAKES: A WIND-TUNNEL STUDY"

Boundary-Layer Meteorology, Vol. 136, 2010, pp. 515-533.

Wind-tunnel experiments were carried out to study turbulence statistics in the wake of a model wind turbine placed in a boundary-layer flow under both neutral and stably stratified conditions. High-resolution velocity and temperature measurements, obtained using a customized triple wire (cross-wire and cold wire) anemometer, were used to characterize the mean velocity, turbulence intensity, turbulent fluxes, and spectra at different locations in the wake. The effect of the wake on the turbulence statistics is found to extend as far as 20 rotor diameters downwind of the turbine. The velocity deficit has a nearly axisymmetric shape, which can be approximated by a Gaussian distribution and a power-law decay with distance. This decay in the near-wake region is found to be faster in the stable case. Turbulence intensity distribution is clearly non-axisymmetric due to the non-uniform distribution of the incoming velocity in the boundary layer. In the neutral case, the maximum turbulence intensity is located above the hub height, around the rotor tip location and at a distance of about 4-5.5 rotor diameters, which are common separations between wind turbines in wind farms. The enhancement of turbulence intensity is associated with strong shear and turbulent kinetic energy production in that region. In the stable case, the stronger shear in the incoming flow leads to a slightly stronger and larger region of enhanced turbulence intensity, which extends between 3 and 6 rotor diameters downwind of the turbine location. Power spectra of the streamwise and vertical velocities show a strong signature of the turbine blade tip vortices at the top tip height up to about 1-2 rotor diameters. This spectral signature is stronger in the vertical velocity component. At longer downwind distances, tip vortices are not evident and the von Karman formulation agrees well with the measured velocity spectra.

Chamorro, L. P., Arndt, R. and Sotiropoulos, F.

"TURBULENCE PATTERNS AROUND A LARGE WIND FARM"

AIAA Paper 2011-0457, January 2011, Orlando, FL.

A wind-tunnel investigation was performed at the St. Anthony Falls Laboratory atmospheric boundary layer wind tunnel to study fundamental properties of the turbulent flow around a perfectly staggered wind turbine array. The staggered wind farm consisted on a series of 10 rows by 2-3 columns of miniature wind turbines spaced 5 and 4 rotor diameters in the streamwise and spanwise directions, respectively. The wind turbine array was placed in a boundary layer flow developed over a smooth surface under neutrally stratified conditions. Cross-wire anemometry was used to obtain high

resolution measurements of streamwise and vertical velocity components at locations within and above the wind farm. Results show that the staggered configuration is much more efficient in terms of momentum transfer from the background flow to the turbines compared to the case of an aligned wind turbine array under similar turbine separations in the streamwise and spanwise directions. This led to improved power output of the overall wind farm. A simplified analysis suggests that the change of power in the two configurations is on the order of 10 percent. Maximum levels of turbulence intensity in the wind farm were found to be very similar to that of observed in the wake of a single wind turbine, differing substantially with that observed in an aligned configuration under similar spacings. The dramatic changes in momentum and turbulence characteristics in the two configurations shows the importance of turbine layout in engineering design. Lateral homogenization of the turbulence statistics above the wind farm allows the development of simple parameterizations for the adjustment of flow properties, like the case of a surface roughness transition. The development of an internal boundary layer was observed above the wind farm. In this layer, flow statistics are affected by the background flow and wind turbines. The adjustment of the flow in this layer is much slower in the staggered situation (respect to its aligned counterpart) which implies change in the momentum/power available at turbine locations.

Chamorro, L. P., Troolin, D., Lee, S.-J., Arndt, R. E. A. and Sotiropoulos, F.

"THREE-DIMENSIONAL FLOW VISUALIZATION IN THE WAKE OF A MINIATURE AXIAL-FLOW HYDROKINETIC TURBINE"

Experimental Fluids, Vol. 54, 2013, pp. 1459-1470.

Three-dimensional 3-component velocity measurements were made in the near wake region of a miniature 3-blade axial-flow turbine within a turbulent boundary layer. The model turbine was placed in an open channel flow and operated under subcritical conditions ($Fr = 0.13$). The spatial distribution of the basic flow statistics was obtained at various locations to render insights into the spatial features of the wake. Instantaneous and phase-averaged vortical structures were analyzed to get insights about their dynamics. The results showed a wake expansion proportional to the one-third power of the streamwise distance, within the first rotor diameter. Wake rotation was clearly identified up to a distance of roughly three rotor diameters. In particular, relatively high tangential velocity was observed near the wake core, but it was found to be nearly negligible at the turbine tip radius. In contrast, the radial velocity showed the opposite distribution, with higher radial velocity near the turbine tip and, due to symmetry, negligible at the rotor axis. Larger turbulence intensity was found above the hub height and near the turbine tip. Strong coherent tip vortices, visualized in terms of the instantaneous vorticity and the lambda sub two criterion, were observed within the first rotor diameter downstream of the turbine. These structures, influenced by the velocity gradient in the boundary layer, appeared to lose their stability at distances greater than two rotor diameters. Hub vortices were also identified. Measurements did not exhibit significant tip-hub vortex interaction within the first rotor diameter.

Champniss, G. A.

"AIR TRAFFIC MANAGEMENT - THE IMPACT AT THE AIRPORT"

Proceedings of Spring Convention, Royal Aeronautical Society, London, England, May 1982

The introduction of wide-bodied aircraft has led to the adoption of increased separation standards to minimize the effects of wake turbulence. This use of increased separation standards, while of relatively minor significance when the total number of movements by wide bodied aircraft is low, results in a significant reduction in the sustainable capacity of a dedicated landing runway as the proportion of such aircraft increases. The reduction of separation standards currently in use without adverse effects on safety may be achieved by means of more efficient airport surface movement guidance and control, which optimizes the capacity of a given runway. The aircraft whose impact will be most strongly felt are the 757, 767, and 737, all new generation airliners capable of Category III visibility conditions operations which will require airport facilities to accommodate their expanded capabilities.

Chan, A. S., Dewey, P. A., Jameson, A., Liang, C. and Smits, A. J.

"VORTEX SUPPRESSION AND DRAG REDUCTION IN THE WAKE OF COUNTER-ROTATING CYLINDERS"

Journal of Fluid Mechanics, Vol. 679, 2011, pp. 343-382.

The flow over a pair of counter-rotating cylinders is investigated numerically and experimentally. It is demonstrated that it is possible to suppress unsteady vortex shedding for gap sizes from one to five cylinder diameters, at Reynolds numbers from 100 to 200, expanding on the more limited work of Chan and Jameson. The degree of unsteady wake suppression is proportional to the speed and the direction of rotation, and there is a critical rotation rate where a complete suppression of flow unsteadiness can be achieved. In the doublet-like configuration at higher rotational speeds, a virtual elliptic body that resembles a potential doublet is formed, and the drag is reduced to zero. The shape of the elliptic body primarily depends on the gap between the two cylinders and the speed of rotation. Prior to the formation of the elliptic body, a second instability region is observed, similar to that seen in studies of single rotating cylinders. It is also shown that the unsteady wake suppression can be achieved by rotating each cylinder in the opposite direction, that is, in a reverse doublet-like configuration. This tends to minimize the wake interaction of the cylinder pair and the second instability does not make an appearance over the range of speeds investigated here.

Chan, K. R., Dean-Day, J., Bowen, S. W. and Bui, T. P.

"TURBULENCE MEASUREMENTS BY THE DC-8 METEOROLOGICAL MEASUREMENT SYSTEM"

Geophysical Research Letters, Vol. 25, No. 9, May 1998, pp. 1355-1358

The instrumentation of a new MMS on the NASA DC-8 aircraft is briefly described. A method to compute the turbulent dissipation rate is discussed considering some apparent inconsistencies between high and medium altitude aircraft data and available theory. Examples of turbulence

measurements during encounters of a wake vortex, a field of wave clouds, and persistent contrails are illustrated.

Chan, P. W.

"MEASUREMENT OF TURBULENCE INTENSITY PROFILE BY A MINI-SODAR"

Meteorological Applications, Vol. 15, 2008, pp. 249-258.

Low-level turbulence can bring about rapid bumps and jolts to an aircraft. In severe turbulence, the aircraft may suffer momentary loss of control. In accordance with the practice of ICAO, turbulence intensity is expressed in terms of the cube root of the eddy dissipation rate (EDR). Measurement of the EDR is an important component in the provision of turbulence alerting services for arriving and departing aircraft at an airport. This article describes a method to calculate the EDR profile using the wind measurements from a ground-based mini-sodar located near the Hong Kong International Airport (HKIA). The method makes use of the vertical wind data at 0.25 or 0.5 Hz provided by the mini-sodar (depending on the maximum measurement range) and searches for the inertial sub-range in the frequency spectrum of the vertical wind. The accuracy of the wind and EDR measurements of the mini-sodar is first established by comparison with meteorological tower data in a field experiment. The potential application of the EDR profiles in terrain-disrupted airflow at HKIA is then demonstrated through two case studies. The EDR profiles obtained from the mini-sodar are found to be of good quality and could be useful in the monitoring of low-level turbulence for aviation applications.

Chan, P. W.

"DETERMINATION OF RICHARDSON NUMBER PROFILE FROM REMOTE SENSING DATA AND ITS AVIATION APPLICATION"

14th International Symposium for the Advancement of Boundary Layer Remote Sensing, published in IOP Conf. Series: Earth and Environmental Science, Vol. 1, 2008, pp. 012043-1 - 012043-8.

A number of remote-sensing wind-measuring instruments, such as LIDAR and radar wind profilers, have been set up in the vicinity of the Hong Kong International Airport (HKIA) for monitoring of low-level windshear and turbulence. The combined usage of wind data from a radar wind profiler and boundary layer temperature profiles from a ground-based microwave radiometer in turbulence application is studied in this paper. Data collected in a field experiment of the radiometer conducted in Hong Kong in February 2006 were used to obtain the Richardson number profile up to 1.5 km above ground. Two examples of atmospheric turbulence reported by the pilots are considered. The Richardson number profiles are found to capture the turbulence events reasonably well. The evolution of these profiles and airflow disruption by the nearby terrain as a possible cause of the turbulence will also be discussed.

Chan, P. W.

"LIDAR-BASED TURBULENCE INTENSITY FOR AVIATION APPLICATIONS"

In *Aviation Turbulence*, edited by R. Sharman and T. Lane, Chapter 9, 2016, Springer International Publishing Switzerland, pp. 193-209.

Turbulence could increase the workload of pilots, and timely provision of turbulence information would be beneficial to aircraft operation. This paper summarizes the use of a Doppler Light Detection and Ranging (LIDAR) system to measure turbulence intensity at an operating airport. The cube root of eddy dissipation rate (ERD) is used for representing the turbulence intensity, according to the requirement of the International Civil Aviation Organization (ICAO). The quality of EDR so calculated is established by comparing with the aircraft data. Examples of EDR maps based on conical scans of the LIDAR are presented. The EDR maps so obtained should be useful for aviation operations, and the EDRs calculated from the glide-path scans of the LIDAR may be used for turbulence alerting applications.

Chan, P. W.

"PERFORMANCE AND AVIATION APPLICATIONS OF MINISODARS AT HONG KONG INTERNATIONAL AIRPORT"

Meteorological Applications, Vol. 21, 2014, pp. 62-73.

The performance and aviation application of mini-sodars at Hong Kong International Airport are discussed in this paper. There are two mini-sodars at the airport and they have been in use for more than 2 years. The data availability at various measurement heights shows that the mini-sodars in general provide reasonably good coverage for aviation applications. The mini-sodar's wind data compare well with other measurements, including the anemometer data and LIDAR (light detection and ranging) data. The applications of mini-sodar data are then described. They are found to provide useful indications of low-level windshear, mechanical turbulence associated with complex terrain, and downburst associated with a thunderstorm. Through these case studies, the mini-sodars are found to provide good supplementary data to other remote sensing meteorological instruments, such as LIDAR and radar, in the monitoring of low-level wind changes that may be encountered by the aircraft.

Chan, P. W. and Li, C. M.

"COMPARISON OF TURBULENCE INTENSITY COMPUTED FROM LIDAR AND AIRCRAFT DATA"

24th International Laser Radar Conference, June 2008, Boulder, CO.

The glide-path scans of the LIDARs at the Hong Kong International Airport (HKIA) are used to calculate the eddy dissipation rate (EDR), the internationally adopted metric for turbulence reporting/alerting, by using the structure function approach based on the radial velocity data. The EDR so determined is compared with the turbulence intensity calculated from the Quick Access Recorder (QAR) data of transport category commercial aircraft landing at HKIA. The two sets of EDR data are well correlated, though there is considerable spread of the data points in the scatter plot. The spread may be related to

the discrepancy between the LIDAR velocity data and the actual wind encountered by the aircraft, as well as the transient and sporadic nature of the turbulence itself. Two examples of the EDR profiles from the LIDAR and the QAR data are discussed.

Chan, P. W. and Li, C. M.

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Chan, W. M., Shariff, K. and Pulliam, T. H.

"INSTABILITIES OF TWO-DIMENSIONAL INVISCID COMPRESSIBLE VORTICES"

Journal of Fluid Mechanics, Vol. 253, 1993, pp. 173-209.

The linear stability and subsequent nonlinear evolution and acoustic radiation of a planar inviscid compressible vortex is examined. Linear-stability analysis shows that vortices with smoother vorticity profiles than the Rankine vortex considered by Broadbent & Moore (1979) are also unstable. However, only neutrally stable waves are found for a Gaussian vorticity profile. The effects of entropy gradient are investigated and for the particular entropy profile chosen, positive average entropy gradient in the vortex core is destabilizing while the opposite is true for negative average entropy gradient. The linear initial-value problem is studied by finite-difference methods. It is found that these methods are capable of accurately computing the frequencies and weak growth rates of the normal modes. When the initial condition consists of random perturbations, the long-time behavior is found to correspond to the most unstable normal mode in all cases. In particular, the Gaussian vortex has no algebraically growing modes. This procedure also reveals the existence of weakly decaying and neutrally stable waves rotating in the direction opposite to the vortex core, which were not observed previously. The nonlinear development of an elliptic-mode perturbation is studied by numerical solution of the Euler equations. The vortex elongates and forms shocklets; eventually, the core splits into two corotating vortices. The individual vortices then gradually move away from each other while their rate of rotation about their mid-point slowly decreases. The acoustic flux reaches a maximum at the time of fission and decreases as the vortices move apart.

Chang, C.-C.

"A SIMPLIFIED METHOD OF OBTAINING DRAG OF A HIGH-SPEED BODY FROM WAKE SURVEYS"

Journal of the Aeronautical Sciences, Vol. 15, No. 2, February 1948, pp. 123-127.

Jones' drag integral equation is re-examined in the light of the known experimental fact that nearly constant stagnation temperature exists across the wake of a body moving at high speed in air. It is found that the integrand of the equation can be separated into the product of two functions -- namely, one function containing the ratio of the static to total head pressure at the measuring station in the body's wake and the second function containing two similar pressure ratios that correspond to conditions far up and far downstream along the same stream line. Each of the two functions can be conveniently plotted in a graph. With the aids of such graphics, this analysis makes the pitot-transverse method practical and easy to apply in determining drag of flight at subsonic speed. An example of application is shown. Some justifications of the assumption are made, and the limitations of application are explained. It is further found that the method can be applied approximately to flow around a two-dimensional body with shock and possibly to supersonic flow, as long as at and behind the measurement station no shock waves of appreciable strength exist. Of course, some development work has to be done before this method can be successfully applied to the supersonic case.

Chang, J. W.

"NEAR-WAKE CHARACTERISTICS OF AN OSCILLATING NACA 4412 AIRFOIL"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1240-1243

This experimental study was carried out to measure phase-averaged mean velocity and its turbulent intensity in the near-wake region of an oscillating NACA 4412 airfoil at the Reynolds numbers $Re = 5.3 \times 10,000$, $1.9 \times 100,000$, and $4.1 \times 100,000$. All cases in these measurements show that the velocity defects were coupled with both the camber effect and the Reynolds-number effect and that the Reynolds-number effect may be associated with the laminar or turbulent boundary layer on the airfoil surface. The near-wake characteristics of an oscillating NACA 4412 airfoil are insensitive to Reynolds numbers between $Re = 1.9 \times 100,000$ and $4.1 \times 100,000$. At $Re = 5.3 \times 10,000$, test results show that the magnitude and width of the velocity defect are much larger than those in the range between $Re = 1.9 \times 100,000$ and $4.1 \times 100,000$. A critical value of the Reynolds number in the near wake of an oscillating NACA 4412 airfoil, which includes either cases of lamina separation or cases of no separation or turbulent separation, exists in the range between $5.3 \times 10,000$ and $1.9 \times 100,000$. The near-wake characteristics of the NACA 4412 airfoil at $\alpha = 0$ deg are considerably different depending on motion direction due to the slightly sharper-edged nose shape of the lower surface of the NACA 4412 airfoil compared to the nose shape of the upper surface as well as the phase lag in the near-wake region of the airfoil oscillation.

Chang, J. W. and Park, S. O.

"AN EXPERIMENTAL STUDY OF TIP VORTEX ROLL-UP OF AN OSCILLATING WING"

AIAA Paper No. 1999-0142, Reno, NV, January 1999.

An experimental study was made to quantitatively examine the tip vortex roll-up in the near field of an oscillating wing. A NACA 0012 rectangular planform wing with an aspect ratio of 4.0 was mounted on the bottom of the wind tunnel test section, and the wing was sinusoidally pitched about the quarter chord. Both the mean incidence and the amplitude of oscillation were set at 15 degrees. Measurements by using a triple hot-film probe were made for the case of the reduced frequency of 0.09 and the chord Reynolds number of 34,000. The phase-averaged mean velocity, vorticity, and turbulence intensity profiles in the wing tip vortex region are presented and variations of these with respect to the instantaneous angle of attack are discussed in detail. 'Phase-lag' compensated variation of the circulation of the tip vortex during the cycle of oscillation is also included.

Chang, J. W. and Yoon, Y. H.

"CAMBER EFFECTS ON THE NEAR WAKE OF OSCILLATING AIRFOILS"

Journal of Aircraft, Vol. 39, No. 4, July-August 2002, pp. 713-716.

Phase-averaged mean velocity and its fluctuations in the near wake of oscillating airfoils are presented. The near-wake characteristics of a NACA 0012 airfoil at + and - instantaneous angle of attack AOA show symmetric profiles about the X axis because of the symmetry of motion and airfoil shape. The velocity profiles and the turbulent intensity profiles of a NACA 4412 airfoil have small difference with those of a NACA 0012 airfoil except upstroke motion case at a negative angle of attack. These are attributable to either similar upper shape or the motion direction of the leeward surface, which result in the flow attachment to the surface. On the other hand, the significant difference of near-wake characteristics between NACA 0012 and NACA 4412 airfoil is observed in the case of upstroke motion at negative angle of attack. It is found that the streamwise velocity and turbulent intensity of the NACA 4412 airfoil in the wake region of lower surface are considerably large. These differences in streamwise velocity and turbulence intensity of two airfoils are caused by the different lower shape and the motion direction.

Chang, N. A., Choi, J., Yakushiji, R. and Ceccio, S. L.

"CAVITATION INCEPTION DURING THE INTERACTION OF A PAIR OF COUNTER-ROTATING VORTICES"

Physics of Fluids, Vol. 24, 2012, pp. 014107-1 - 014107-15.

Pairs of unequal strength, counter-rotating vortices were produced to examine the inception and dynamics of vortex cavitation as the vortices undergo a long wavelength instability. The instability causes the weaker, secondary vortex to be turned and stretched by the stronger primary vortex. Folding and stretching of the secondary vortices result in sharp reductions of the core pressure. Here, these sharp and transient reductions in the secondary vortex core pressure produced incipient cavitation at static pressures that were as much as 20 times higher than that required for inception in the core of the unstretched secondary vortex. In addition, most nuclei measured were of the order of 1 micron in size, which requires tension on the order of 100 kPa for cavitation inception to occur. The flow parameters

that lead to the instability and cavitation inception in the secondary vortex are examined, and the measured event rates are correlated to freestream nuclei populations and static pressure. These measurements, combined with observations of the elongated bubbles themselves, suggest that stretching produced large tensions in the core of the secondary vortex due to both a reduction in the secondary vortex core size and the creation of a jetting flow in the vortex core.

Chang, N., Ganesh, H., Yakushiji, R. and Seccio, S. L.

"TIP VORTEX CAVITATION SUPPRESSION BY ACTIVE MASS INJECTION"

Journal of Fluids Engineering, Vol. 133, November 2011, pp. 111301-1 to 111301-11.

Injection of water and aqueous polymer solutions in to the core of a trailing vortex was found to delay the inception of tip vortex cavitation (TVC). Optimal levels of mass injection reduced the inception cavitation number from 3.5 to 1.9, or a reduction of 45 percent. At the optimal fluxes, injection of water alone produced a reduction of 35 percent, and the addition of polymer solution led to a reduction of 45 percent. Stereo particle velocimetry was employed to examine the flow fields in the region of TVC inception and infer the average core pressure, and planar PIV was used to examine the flow unsteadiness in this region. The time-averaged pressure coefficients for the vortex core pressure were estimated and compared to the pressure needed for TVC inception and full development. Measurement of flow variability in the TVC inception region indicated that relatively low fluxes of mass injection in the TVC roll-up region led to a substantial decrease in flow unsteadiness in the core region near the observed location of inception, and this corresponded to a substantial decrease in the inception pressure. Increased injection of water or polymer solutions led to a modest increase in the average vortex core radius, which was discernable in the measured pressure needed for developed cavitation.

Chang, T. Y., Hertzberg, J. R. and Kerr, R. M.

"THREE-DIMENSIONAL VORTEX/WALL INTERACTION: ENTRAINMENT IN NUMERICAL SIMULATION AND EXPERIMENT"

Physics of Fluids, Vol. 29, No. 1, January 1997, pp. 57-66.

Three-dimensional interactions between an elliptic vortex ring and two no-slip parallel walls are visualized in a numerical simulation and an experiment. The vortex ring induces a surface vorticity layer on the wall which reconnects with the vortex ring. During the interaction core-area-varying axial waves are generated and carry the surface layer away from the wall. The vortex ring then becomes two tornado-like structures with strong upward helical flows near the wall surface, which provides entrainment of the surface fluid into the vortex structure. Similarities between the entrainment mechanisms of vorticity in the simulation and dye in the experiment from the surface layer are identified.

Chao, H., Gu, Y., Tian, P., Zheng, Z. and Napolitano, M.

"WAKE VORTEX DETECTION WITH UAV CLOSE FORMATION FLIGHT"

AIAA Paper 2015-2396, June 2015, Dallas, TX.

Birds fly in formation to benefit from the upwash wake vortices created by their peer leader. Similar strategies can be employed on aircraft for fuel saving or for range extension. However, further understanding of wake vortices in the near field and mid field is needed for close formation flight (less than 10 wingspans). This paper introduces a new method for wake vortex detection using small UAV formation. A NonLinear Dynamic Inversion (NLDI) based formation control law is adapted to the WVU Phastball UAV platform. The designed controller showed good tracking performance during close formation flight (5-10 wingspans) with typical errors of less than 3 meters during straight legs. Then, multiple sensor measurements from leader-follower UAV formation flights were used for the wake vortex detection, including angle of attack, angle of sideslip, accelerometers, and gyros. The collected flight data showed the feasibility of using UAV formation for the wake encounter detection.

Chappell, S. and Angland, D.

"ACTIVE CONTROL OF A WING TIP VORTEX WITH A DIELECTRIC BARRIER DISCHARGE PLASMA ACTUATOR"

AIAA Paper No. 2012-2952, June 2012, New Orleans, LA.

An experimental investigation has been conducted into the active control of a wing tip vortex with a dielectric barrier discharge plasma actuator. The actuator was placed around the wing tip with the momentum added in the opposite direction to that of the cross-stream flow. Particle image velocimetry measurements were performed on a low aspect ratio rounded tip NACA 0015 wing in a low-speed wind tunnel at a maximum Reynolds number of 280,000, based on the wing chord. Experiments were performed at various angles of attack. The current strength of the plasma actuator limited the maximum freestream velocity to 15 m/s. For low angles of attack (2 and 6 degrees), the near field results showed an increase in vortex size and a reduction in the core circulation when control was applied. The effectiveness of the actuator reduced with freestream velocity and angle of attack. The use of the plasma actuator was found to increase the velocity fluctuations close to the surface of the wing. At an angle of attack of 14 degrees, the actuator resulted in a smaller vortex and an increase in the core circulation. It was hypothesized that at this high angle of attack, the vorticity generated at the suction side electrodes was fed into the core, increasing the strength of the tip vortex. The results show that the potential of the plasma actuator for the near field control of the tip vortex is promising provided the angle of attack is low.

Charney, J. J., Kaplan, M. L., Lin, Y-L. and Pfeiffer, K. D.

"A NEW EDDY DISSIPATION RATE FORMULATION FOR THE TERMINAL AREA PBL PREDICTION SYSTEM (TAPPS)"

AIAA Paper No. 2000-0624, Reno, NV, January 2000

The TAPPS employs the MASS model to produce mesoscale atmospheric simulations in support of the Wake Vortex project at Dallas Fort-Worth International Airport (DFW). A post-processing scheme uses the simulated three-dimensional atmospheric characteristics in the planetary boundary layer (PBL) to calculate the turbulence quantities most important to the dissipation of vortices: turbulent kinetic energy and eddy dissipation rate. TAPPS will ultimately be employed to enhance terminal area productivity by providing weather forecasts for the Aircraft Vortex Spacing System (AVOSS). The post-processing scheme utilizes experimental data and similarity theory to determine the turbulence quantities from the simulated horizontal wind field and stability characteristics of the atmosphere. Characteristic PBL quantities important to these calculations are determined based on formulations from the Blackadar PBL parameterization, which is regularly employed in the MASS model to account for PBL processes in mesoscale simulations. The TAPPS forecasts are verified against high-resolution observations of the horizontal winds at DFW. Statistical assessments of the error in the wind forecasts suggest that TAPPS captures the essential features of horizontal winds with considerable skill. Additionally, the turbulence quantities produced by the post-processor are shown to compare favorably with corresponding tower observations.

Chatelain, P., Curioni, A., Bergdorf, M., Rossinelli, D., Andreoni, W. and Koumoutsakos, P.

"VORTEX METHODS FOR MASSIVELY PARALLEL COMPUTER ARCHITECTURES"

VECPAR 2008, Lecture Notes in Computer Science, Vol. 5336, 2008, pp. 479-489.

We present Vortex Methods implemented in massively parallel computer architectures for the Direct Numerical Simulations of high Reynolds numbers flows. Periodic and non-periodic domains are considered leading to unprecedented simulations using billions of particles. We discuss the implementation performance of the method up to 16k IBM BG/L nodes and the evolutionary optimization of long wavelength instabilities in aircraft wakes.

Chatelain, P., Curioni, A., Bergdorf, M., Rossinelli, D., Andreoni, W. and Koumoutsakos, P.

"MASSIVELY PARALLEL VORTEX PARTICLE SIMULATIONS OF WAKES"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

We present the Direct Numerical Simulations of high Reynolds numbers aircraft wakes employing vortex methods. The simulations are based on a hybrid particle-mesh formulation and its scalable implementation for massively parallel distributed-memory computers. We develop efficient domain decompositions, Fourier parallel solvers and optimized data mappings that rely on the Message Passing Interface (MPI). The software is tested and run on the IBM Blue Gene/L parallel architecture using up to 16k nodes on unprecedented problem sizes of several billions of particles. We study the growth of the medium wavelength instability for counter-rotating vortex pairs as a wake alleviation mechanism. The calculation used a long domain (10 spans) and random noise to initiate the instability at Re of 6000.

This 1.5 billion particle system was run on 4096 IBM BG/L nodes and constitutes the largest DNS ever achieved for a vortex particle method. Ongoing code development includes further optimization for Blue Gene/L and modifications for the multicore architecture of Blue Gene/P. The code currently uses periodic boundary conditions in directions transverse to the wake; it is being extended to more efficient unbounded ones.

Chatelain, P., Curioni, A., Bergdorf, M., Rossinelli, D., Andreoni, W. and Koumoutsakos, P.

"BILLION VORTEX PARTICLE DIRECT NUMERICAL SIMULATIONS OF AIRCRAFT WAKES"

Compu. Methods Applied Mech. Engineering, Vol. 197, 2008, pp. 1296-1304

We present the Direct Numerical Simulations of high Reynolds numbers aircraft wakes employing particle methods. The simulations involve a highly efficient implementation of vortex methods on massively parallel computers, enabling unprecedented simulations using billions of particles. The method relies on the Lagrangian discretization of the Navier-Stokes equations in velocity-velocity form and relies on remeshing of the particles to ensure the convergence of the method. The results include unprecedented Direct Numerical Simulations of the onset and the evolution of multiple wavelength instabilities induced by ambient noise in aircraft vortex wakes at $Re = 6000$.

Chatelain, P., Gazzola, M., Kern, S. and Koumoutsakos, P.

"OPTIMIZATION OF AIRCRAFT WAKE ALLEVIATION SCHEMES THROUGH AN EVOLUTION STRATEGY"

9th International Meeting High Performance Computing for Computational Science, Lecture Notes in Computer Science, Vol. 6449, June 2010, Berkeley, CA, pp 210-221.

We investigate schemes to accelerate the decay of aircraft trailing vortices. These structures are susceptible to several instabilities that lead to their eventual destruction. We employ an Evolution Strategy to design a lift distribution and a lift perturbation scheme that minimize the wake hazard. The performance of a scheme is measured as the reduction of the mean rolling moment that would be induced on a following aircraft; it is computed by means of a Direct Numerical Simulation using a parallel vortex particle code. We find a configuration and a perturbation scheme characterized by an intermediate wavelength about 4.64, necessary to trigger medium wavelength instabilities between tail and flap vortices and subsequently amplify long wavelength modes.

Chatterjee, A. and Janus, J. M.

"ON THE USE OF A WAKE-INTEGRAL METHOD FOR COMPUTATIONAL DRAG ANALYSIS"

AIAA Paper No. 95-0535, Jan. 1995, Reno, NV.

In this expository paper, a practical software implementation for calculating induced drag based on a wake-integral approach is presented. The procedures required to produce satisfactory performance predictions are disclosed. The flow solver used to numerically simulate the flowfield about the

geometries studied herein is based on a finite-volume method to solve the three-dimensional Euler equations. Interface fluxes are determined using a high-resolution Riemann scheme. The post-processing software is versatile and is capable of handling different grid topologies on the transverse plane. To test the software, an elliptic wing is analyzed and a comparison is made with lifting-line theory. Further tests are conducted with isolated rectangular wings of varying aspect ratios under different lifting conditions. Finally, the software is applied to some wing-body combinations (tip-engine configurations) and a comparison is made with experimental results.

Chattot, J.-J.

"HELICOIDAL VORTEX MODEL FOR STEADY AND UNSTEADY FLOWS"

AIAA Paper No. 2004-0829, Reno, NV, January 2004

A helicoidal vortex model is used to predict the flow past the blades of a wind turbine. As the tip speed ratio varies, the environment in which the blades operate varies, and for low enough TSR, the local angle of attack will be larger than the incidence of maximum lift. The problem becomes highly nonlinear and it is shown that adding an artificial viscosity term to the equation allows the iterative algorithm to converge toward a smooth solution that is physically acceptable. The introduction of unsteady effects is useful to understand the cyclic forces and moments due to yaw or tower interaction, both for the design of blades to account for fatigue and for power output prediction. The 2-D impulsively plunging plate problem is solved with a semi-implicit scheme and the integral and numerical solutions compared and shown to be in excellent agreement. A 2-D test case to study the convection of a periodic shedding of vorticity downstream of a blade element is analyzed using the same semi-implicit algorithm and a stretched mesh like that used to model a turbine vortex sheet. The scheme captures accurately the vorticity distribution in the wake. Finally, the scheme is applied to the simulation of the NREL two-bladed rotor in yaw to assess the validity of the approach.

Chattot, J.-J.

"TOWER SHADOW MODELIZATION WITH HELICOIDAL VORTEX METHOD"

AIAA Paper No. 2007-420, Reno, NV, January 2007

The helicoidal vortex model developed by the author is compared with data of the National Renewable Energy Laboratory (NREL) Unsteady Aerodynamics Experiment (UAE). The B Sequence has been used for this purpose. It corresponds to the 'downward configuration' where the blades cross the tower shadow. Several cases have been analyzed with wind speeds of $V = 5, 7, 10$ and 12 m/s and yaw angles of up to 30 degrees. The results indicate that the modelization of the tower shadow gives good results in the range of applicability of the vortex model, at a low computer cost, and demonstrates further the versatility of this approach.

Chawla, K. and Chow, C.-Y.

"ACOUSTIC CONTROL OF VORTICES"

AIAA Paper No. 1989-1042, San Antonio, TX, April 1989

Effect of traveling acoustic waves on vortices is analyzed. Computational models are presented for two-, three- and four-vortex systems in the presence of acoustic waves; models can be generalized for any number of vortices. Time dependent vortex trajectories are presented for a few representative cases. It is shown that for different systems, at certain acoustic frequencies, amplitude of vortex displacement away from the mean path is substantial, implying wave induced velocity may play a significant role in re-orienting vortices. Vortex trajectories indicate that for systems with more than two vortices, the amplitude of vortex displacement away from the mean path does not have discrete maxima/minima; it fluctuates between higher and lower values, as the systems are subjected to a range of frequencies.

Chen, A. L., Jacob, J. D. and Savas, O.

"DYNAMICS OF COROTATING VORTEX PAIRS IN THE WAKES OF FLAPPED AIRFOILS"

J. Fluid Mech., Vol. 382, March 1999, pp. 155-193

The behavior of a pair of corotating vortices in the wake of a flapped airfoil is experimentally studied in a water towing tank. Reynolds numbers based on total circulation of the vortices range from $1.0 \times 10,000$ to $6.4 \times 10,000$. Planar velocity vector fields and their gradients are derived from PIV images using an adaptive Lagrangian parcel tracking algorithm. Isovorticity surfaces are extracted from time series of planar vorticity data. The behavior of the vortices is tracked by using various moments of both the probability density distribution and the spatial distribution of their streamwise vorticity. All vortices show a Lamb-Oseen circulation distribution when they are clearly identifiable. Further, vortices from the flapless wing exhibit Lamb-Oseen velocity and vorticity distributions with slow growth. All corotating vortex pairs are observed to merge at about 0.8 orbit periods. First-order statistics of the flow field remain invariant during the merger. The higher-order moments of the vorticity distribution show strong time dependence, which implies three-dimensionality of the flow resulting from vortex stretching. The strengths of the individual vortices before merger are constant, and the total circulation before and after merger remains constant within the range of observations. The trajectory of the center of vorticity remains unaffected by the merger process. The merger is preceded by a splitting of the weaker vortex into filaments which, depending on the relative strengths of the vortices, can occur in the radial direction, the axial direction, or a combination of the two. Mechanisms contributing to the merger dynamics are discussed.

Chen, C. and Prasad, J. V. R.

"A SIMPLIFIED INFLOW MODEL OF A HELICOPTER ROTOR IN FORWARD DESCENT"

AIAA Paper No. 2005-0622, Reno, NV, January 2005

A helicopter rotor in a descent flight encounters its own wake, resulting in a doughnut-shaped ring around the rotor disk, known as the Vortex Ring State (VRS). To investigate flight dynamic behavior of a helicopter in VRS condition, a new inflow model called the 'Vortex Rings Model' has recently been proposed for axial descent. The current study extends the Vortex Rings Model to the case of inclined descent, i.e., forward flight descent. The new model is validated using flight test results of the Dauphin helicopter from the literature. It is shown that the VRS boundary prediction using the new model correlates well with flight test results of the Dauphin helicopter.

Chen, C. and Prasad, J. V. R.

"SIMPLIFIED ROTOR INFLOW MODEL FOR DESCENT FLIGHT"

Journal of Aircraft, Vol. 44, No. 3, May-June 2007, pp. 936-944.

A simplified inflow model called the 'ring vortex model' is developed for a rotor in descent condition. The ring vortex model accounts for interaction between rotor wake and surrounding airflow in descent flight by using a series of vortex rings along the rotor wake. Important features of the ring vortex model are illustrated in detail, including the convection speed, the vortex strength, and the number of vortex rings. An augmentation to total mass flow parameter in the existing inflow equation is proposed to create a steady-state transition between the helicopter and the windmill branches. With the ring vortex model, it is feasible to predict rotor inflow over a wide range of descent conditions. Numerical results show good correlation with experimental data for both axial and inclined descent. In addition, the ring vortex model is used to explain the influence of model parameters (such as blade twist and blade taper) on rotor-induced velocity during descent flight.

Chen, C., Wang, Z. and Gursul, I.

"UNSTEADY NATURE OF VORTEX PAIR IN FORMATION FLIGHT"

AIAA Paper 2017-3306, June 2017, Denver, CO.

The interaction of trailing vortices from a leading wing with rigid and flexible downstream wings has been investigated experimentally in an open jet wind tunnel using force measurements, particle image velocimetry measurements, hotwire measurements and deformation measurements. Counter-rotating leading vortex has been found to have substantial meandering when it is close to the tip of the downstream wing. The leading vortex forms a pair with the vortex from the downstream wing, and then exhibits large displacements around the wing tip. This has been found to cause the largest lift fluctuations on the downstream wing. The meandering of the vortex pair occurs at the natural meandering frequency of the isolated vortex, with a low Strouhal number, and is not affected by the frequency of the wing bending oscillations if the downstream wing is flexible. While the displacement of the leading vortex is larger than that of the trailing vortex, time-dependent variations of the core radius, core vorticity and circulation are evident for the trailing vortex. In contrast, co-rotating vortices do not exhibit any increased meandering.

Chen, C., Wang, Z. and Gursul, I.

"EXPERIMENTS ON TIP VORTICES INTERACTING WITH DOWNSTREAM WINGS"

Experiments in Fluids, Vol. 59, 2018, pp. 82-1 to 82-24.

The interaction of meandering tip vortices shed from a leading wing with a downstream wing was investigated experimentally in a water tunnel using flow visualization, particle image velocimetry measurements, and volumetric velocity measurements. Counter-rotating upstream vortices may exhibit sudden variations of the vortex core location when the wing-tip separation is within approximately twice the vortex core radius. This is caused by the formation of vortex dipoles near the wing tip. In contrast, co-rotating upstream vortices do not exhibit such sensitivity. Large spanwise displacement of the trajectory due to the image vortex is possible when the incident vortex is further inbound. For both co-rotating and counter-rotating vortices, as long as there is no direct impingement upon the wing, there is a little change in the structure of the time-averaged vortex past the wing, even though the tip vortex shed from the downstream wing may be substantially weakened or strengthened. In the absence of the downstream wing, as well as for weak interactions, the most energetic unsteady modes represent the first helical mode.

Chen, C., Wang, Z., Cleaver, D. J. and Gursul, I.

"INTERACTION OF TRAILING VORTICES WITH DOWNSTREAM WINGS"

AIAA Paper 2016-1848, January 2016, San Diego, CA.

The interaction of trailing vortices from a leading wing with a downstream wing and its tip vortex was investigated experimentally in a water tunnel using flow visualization, particle image velocimetry measurements and volumetric velocity measurements. When the wing tip lateral spacing becomes small, sudden variations in the trajectory of the vortices are possible. The tip vortex from the downstream wing can be weakened or strengthened depending on the sign of the upstream vortex. The strongest interactions take place when the upstream vortex directly impinges on the downstream wing and loses its coherency or when the counter-rotating vortex forms a couple with the downstream vortex. In all cases, the axial velocity in the vortex core experiences a sudden acceleration over the downstream wing. Unsteadiness in the upstream vortex was found in the form of first helical mode of displacement. This long wavelength instability in the upstream vortex is not affected much by the interaction and may even excite a similar instability in the downstream vortex.

Chen, H. and Jaworski, J. W.

"VORTEX INTERACTIONS WITH JOUKOWSKI AIRFOIL ON ELASTIC SUPPORTS"

AIAA Paper 2018-2907, June 2018, Atlanta, GA.

The dynamic interaction between a line vortex and a Joukowski airfoil on elastic supports are formulated analytically and computed numerically. The vortex motion and the fluid forces on the airfoil are derived from inviscid potential flow, and the emended Brown and Michael equation describes the

unsteady shedding of vorticity into the wake. Special attention is paid to the limiting cases of flat plate airfoils that are stationary or under prescribed motions for which validation data exist. The present effort extends beyond these restrictions to include the geometric effects of the Joukowski airfoil profile and its aeroelastic influence on the incoming vortex path and the unsteady fluid loading.

Chen, J. H., Cantwell, B. J. and Mansour, N. N.

"THE EFFECT OF MACH NUMBER ON THE STABILITY OF A PLANE SUPERSONIC WAKE"

Phys. Fluids A, Vol. 2, No. 6, June 1990, pp. 984-1004

Recent interest in supersonic combustion and problems of trans-atmospheric flight has prompted research efforts in laminar-turbulent free-shear flow transition. In the present work, the influence of Mach number on the stability of supersonic planar wake flows is investigated to gain insight into the physics of linear, nonlinear, and three-dimensional (3-D) stages of transition. The effect of varying the relative phase difference between a fundamental instability mode and its subharmonic is investigated as a possible means of controlling the evolution of a wake. From a linear stability analysis, it is found that the influence of increasing Mach number is stabilizing, resulting in a growth rate at a Mach number of 3 which is 60% that of an incompressible wake. Direct numerical simulations of the time-dependent compressible Navier-Stokes equations in two and three dimensions are performed for a forced time-developing wake using a spectral collocation method. The results of the two-dimensional (2-D) simulations show the slow rollup of spanwise vortices at high Mach numbers that is attributed to the influence of baroclinic and dilatational effects. Finally, the results of three-dimensional simulations forced with the most unstable Kelvin-Helmholtz wave and a pair of oblique three-dimensional waves show that, depending on the initial phasing between the 2-D and 3-D waves, vortex loops may or may not form as a result of the interaction between the streamwise and spanwise vorticity.

Chen, J. M. and Chang, D.-M.

"UNSTEADY PRESSURE MEASUREMENTS FOR PARALLEL VORTEX-AIRFOIL INTERACTION AT LOW SPEED"

J. Aircraft, Vol. 34, No. 3, May-June 1997, pp. 330-336

Two-dimensional vortex-airfoil interaction at airfoil chord Reynolds number $6 \times 10,000$ is studied experimentally by immersing an instrumented NACA 0012 airfoil downstream of a vortex generator airfoil that pitches in a tailored non-sinusoidal form. A clockwise rotating vortex is generated to approach the target airfoil from left to right. When the vortex interacts with a non-lifting airfoil, it creates rather sharp and local variations of surface pressure in the vicinity of the leading edge. For airfoils at an angle of attack ($\alpha = 5$ and 10 deg), the pressure variations appear to be spread over nearly the entire surface. Nevertheless, a greater magnitude in the amplitude of transient lift is noted on the airfoil at high angle of attack ($\alpha = 10$ deg), primarily because of a low-pressure plateau region formed on the upper surface that occurs when the vortex moves downstream of the trailing edge. The amplitude of transient lift is also found to increase with a reduction in the vertical separation between the vortex generator and the airfoil.

Chen, J. M., Huang, T.-G. and Huang, J.-M.

"LATERAL OSCILLATIONS OF AN AIRCRAFT MODEL AT HIGH ANGLES OF ATTACK"

Journal of Fluids and Structures, Vol. 10, Issue 6, August 1996, pp. 601-614

Lateral oscillations occurring on the aircraft model of NASA TP 1803 at angles of attack ranging from 25 degrees to 60 degrees have been investigated in a low-speed wind tunnel for configurations including fuselage with wing or with a combination of wing and leading-edge extension (LEX). The wind tunnel experiment was conducted in the range of Mach number from 0.1 to 0.2, and the range of the Reynolds number based on the body diameter from $2.8 \times 100,000$ to $5.6 \times 100,000$. The time-varying side force coefficients, which may represent the displacements of oscillation in the lateral direction, were measured to obtain the root-mean square values and the power spectra. Flow visualization of the vortices generated from the forebody, wing and LEX of the model has also been performed in a water tunnel. It was found that the entire system of the flow and the sting-supported model locks-in at the resonant oscillation frequency as the lateral oscillation occurs. The enhancement of the lateral oscillation, as suggested by the water tunnel visualization, seems closely related to the breakdown of the LEX vortices in general and the location of breakdown in particular.

Chen, M., Liu, P., Guo, H. and Qu, Q.

"EFFECT OF SIDESLIP ON HIGH-ANGLE-OF-ATTACK VORTEX FLOW OVER CLOSE-COUPLED CANARD CONFIGURATION"

Journal of Aircraft, Vol. 53, No. 1, January-February 2016, pp. 217-230.

The aerodynamic response to sideslip is crucial for an aircraft's lateral stability, especially for configurations incorporating vortex flow, on which sideslip causes asymmetric vortex behavior and brings extra complexity. In this work, vortex flow over a close-coupled canard configuration under sideslip is simulated using delayed detached-eddy simulation, with the angle of attack varying up to the post stall regime. Sideslip-induced distinctions in both vortex dynamics and canard/wing-vortex interaction are analyzed to explain the nonlinear response of the configuration. The results reveal that the effect of sideslip differs significantly upon different angle-of-attack regimes. At a medium angle of attack, the spanwise extension of the low-pressure area due to windward vortex core expansion results in superior windward lift against the leeward side, but the relatively low pressure retained due to delay of the leeward vortex breakdown is the main motivation that leeward lift surpasses windward at a high angle of attack. The canard vortex trajectory deflected under sideslip induces asymmetric vortex interaction, enhancing the leeward side, which not only leads to an unusual rolling moment toward the higher lift side at a medium angle of attack but also causes an abrupt loss of lateral stability at the post stall angle of attack. A featured demarcation line exists on both the canard and the wing to separate the lift imbalance area, which is found useful in interpreting the nonlinear behavior.

Cheng, H. K.

"AERODYNAMICS OF A RECTANGULAR PLATE WITH VORTEX SEPARATION IN SUPERSONIC FLOW"

Journal of the Aeronautical Sciences, Vol. 22, No. 5, April 1955, pp. 217-226.

A solution is obtained for the supersonic flow field in the tip region of a rectangular flat plate, in which the phenomenon of vortex separation from the side-edge is approximated by introducing into the analytic flow a ray of singularity possessing the vortex behavior. The strength and the location of the vortex singularity, and thus the solution, are determined by imposing additional conditions to the problem, namely, (1) that the flow velocity around the edge be bounded, and (2) that the vortex system be dynamically free. The mathematical model employed in describing the vortex separation phenomenon is essentially the same as that used in the treatment of the leading-edge separation from slender delta wings. The solution exhibits certain general characteristics of side-edge separation which have been observed at low speed for low-aspect-ratio airfoils.

Cheng, J., Tittsworth, J., Gallo, W. and Awwad, A.

"THE DEVELOPMENT OF WAKE TURBULENCE RECATEGORIZATION IN THE UNITED STATES"

AIAA Paper 2016-3434, June 2016, Washington, DC.

This paper describes the background information and provides a status update on a specific aspect of the Federal Aviation Administration (FAA) wake turbulence program known as RECAT (i.e., Recategorization). The fundamental premise of RECAT is that, instead of using the existing FAA Order JO 7110.65 categorical wake turbulence separation minima based on maximum takeoff weight, wake separation can be refined using a more complete set of wake related parameters. This process then leads to a safe reduction of wake turbulence separation minima over those specified in FAA Order JO 7110.65. This paper describes the overall three-phased approach of RECAT, with the ultimate goal of achieving dynamic pairwise separation. Currently, Phase II, or a static pairwise based wake turbulence separation is ready for implementation by the Federal Aviation Administration. The paper describes the analysis approach, including the data sources and severity metrics used in the development of RECAT Phase II.

Cheng, M., Lou, J. and Lim, T. T.

"VORTEX RING WITH SWIRL: A NUMERICAL STUDY"

Physics of Fluids, Vol. 22, 2010, pp. 097101-1 - 097101-9.

In this paper, we use a lattice Boltzmann method to study the effect of swirl on the dynamics of an isolated three-dimensional vortex ring in a viscous incompressible fluid. We focus on a fixed Reynolds number of 800 and vary swirl magnitude and vortex core size. Results show that increasing swirl for a fixed core size or increasing core size for a fixed swirl causes vortex ring to slow down or even travel backward initially. A simplified physical explanation for this dynamic behavior is proposed. Our results further show that while a weak swirl causes vortex filaments to undergo helical winding, a sufficiently

strong swirl transforms these windings into convoluted three-dimensional vortex structure with vortex loops trailing behind it. Each of these vortex loops may reconnect with itself, through the process of vortex reconnection, to form a ringlet.

Cheng, M., Lou, J. and Lim, T. T.

"MOTION OF A VORTEX RING IN A SIMPLE SHEAR FLOW"

Physics of Fluids, Vol. 21, 2009, pp. 081701-1 - 081701-4.

The motion and deformation of a vortex ring in a linear or simple shear flow have been simulated numerically by using the lattice Boltzmann method with multiple relaxation times. The study is motivated by a recent experiment which shows that a vortex ring propagating in a uniform cross flow does not experience Kutta lift and undergo tilting and deformation. The focus of the present study is to examine the effect of a simple shear in a cross flow on the motion of a vortex ring. Numerical approach is adopted here because a truly simple shear flow is difficult to generate experimentally. Our computation shows that a vortex ring tilts and deforms in a simple shear flow, and the tilting can be attributed to the modification of the vorticity distribution of the vortex ring because of the entrainment of background vorticity by the vortex core. It is further shown that although the shear in the flow has the tendency to elongate the vortex ring, the tilting angle of the ring increases with the shear ratio.

Cheng, M., Lou, J. and Luo, L.-S.

"NUMERICAL STUDY OF A VORTEX RING IMPACTING A FLAT WALL"

Journal of Fluid Mechanics, Vol. 660, 2010, pp. 430-455.

We numerically study a vortex ring impacting a flat wall with an angle of incidence I greater than or equal to 0 degrees in three dimensions by using the lattice Boltzmann equation. The hydrodynamic behavior of the ring-wall interacting flow is investigated by systematically varying the angle of incidence I in the range of 0-40 degrees and the Reynolds number Re in the range of 100-1000, where the Reynolds number is based on the translational speed and initial diameter of the vortex ring. We quantify the effects of I and Re on the evolution of the vortex structure in three dimensions and other flow fields in two dimensions. We observe three distinctive flow regimes in the I - Re parameter space. First, in the low-Reynolds-number region, the ring-wall interaction dissipates the ring without generating any secondary rings. Second, with a moderate Reynolds number Re and a small angle of incidence I , the ring-wall interaction generates a complete secondary vortex ring, and even a tertiary ring at higher Reynolds numbers. The secondary vortex ring is convected to the center region of the primary ring and develops azimuthal instabilities, which eventually lead to the development of hairpin-like small vortices through ring-ring interaction. And finally, with a moderate Reynolds number and a sufficiently large angle of incidence I , only a secondary vortex ring is generated. The secondary vortex wraps around the primary ring and propagates from the near end of the primary ring, which touches the wall first, to the far end, which touches the wall last. The rings develop a helical structure. Our

results from the present study confirm some existing experimental observations made in the previous studies.

Chernyshev, S. L., Gaifullin, A. M. and Sviridenko, Y. N.

"CIVIL AIRCRAFT VORTEX WAKE, TSAGI'S RESEARCH ACTIVITIES"

Progress in Aerospace Sciences, Vol. 71, 2014, pp. 150-166.

This paper provides a review of research conducted in TsAGI (Central AeroHydrodynamic Institute) concerning a vortex wake behind an airliner. The research into this area of theoretical and practical importance have been done both in Russia and in other countries, for which these studies became a vital necessity at the end of the 20th century. The paper describes the main methods and ratios on which software systems used to calculate the evolution of a vortex wake in a turbulent atmosphere are based. Verification of calculation results proved their acceptable consistency with the known experimental data. The mechanism of circulation loss in a vortex wake which is based on the analytical solution for the problem of two vortices diffusing in a viscous fluid is also described. The paper also describes the model of behavior of an aircraft which has deliberately or unintentionally entered a vortex wake behind another aircraft. Approximated results of calculations performed according to this model by means of artificial neural networks enabled the researchers to model the dynamics of an aircraft in a vortex wake on flight simulators on-line.

Cheung, K., Jumper, E. J. and Nelson, R. C.

"A DETAILED EXPERIMENTAL FLOW-FIELD STUDY OF AN ISOLATED VORTEX"

AIAA Paper No. 1996-2515, New Orleans, LA, June 1996

This paper presents measurements and analyses of a vortex created by the differential deflection of two adjoining, rectangular wings, used in an experimental study of spiral vortex breakdown. The experimental circulation profile was implemented into a theoretical description of spiral breakdown, motivated by an effort to resolve discrepancies between theoretical and experimental values of the geometric compatibility condition, found to be a constant in spiral vortex breakdown.

Cheung, P. and Lam, C. C.

"OBJECTIVE CALIBRATED WIND SPEED AND CROSSWIND PROBABILISTIC FORECASTS FOR THE HONG KONG INTERNATIONAL AIRPORT"

2nd Aviation, Range and Aerospace Meteorology Special Symposium on Weather-Air Traffic Management Integration, January 2011, Seattle, WA.

Wind is a critical weather element in formulating Terminal Aerodrome Forecast (TAF), especially in tropical cyclone (TC) situations for assessment of crosswind which is known to be one of the top weather factors causing significant flight delay and cancellation at the Hong Kong International Airport

(HKIA). In Hong Kong, the wind and crosswind forecasts and their probability, amongst other weather information, are also contained in the Weather Summary for HKIA which serve as a supplement to TAF to facilitate decision making and cost-benefit analysis by the aviation users. If the forecast uncertainty is high, an alternative scenario is also included in the Weather Summary. To assist aviation forecasters in assessing the possibility of different scenarios in the preparation of wind and crosswind forecasts in TC situations, the Observatory developed objective wind speed and crosswind probabilistic forecasts for HKIA based on the European Centre for Medium-Range Weather Forecasts (ECMWF) Ensemble Prediction System (EPS) outputs. As an enhancement to the aviation weather service, the wind speed and crosswind probabilistic forecasts are also made available to the aviation users up to 36 hours ahead as a trial product. The products are updated every 12 hours at around 21 UTC and 09 UTC upon available of the latest ECMWF EPS data. Recently, post-processing using Model Output Statistics (MOS) technique is applied to the ensemble mean wind speed forecast with a view to calibrating the forecast by removing the systematic bias. This paper describes the methodology for generating the probabilistic forecast and the calibration method. Verification results based on the TC cases in 2009 are also presented.

Chevalier, H.

"FLIGHT TEST STUDIES OF THE FORMATION AND DISSIPATION OF TRAILING VORTICES"

Journal of Aircraft, Vol. 10, No. 1, January 1973, pp. 14-18

A flight test program has been conducted to measure experimentally parameters which describe the characteristics of vortex behavior and their instability. Three basic atmospheric flight conditions were investigated: steady level flight in calm air, steady level flight in light gusting air and light winds, and unsteady flight produced by control surface oscillations in calm air. A DeHavilland Beaver DHC-2 airplane and a Beechcraft T-34B airplane were used in the investigation. Smoke grenades were located near the wing tips of each airplane so that the vortices could be seeded with smoke and thus made visible. This made it possible to photograph the vortices and make measurements from the photographs obtained. The experimental results show wavelengths of vortex instabilities, dissipation time of trailing vortices, effects of atmospheric current or gust, and the effect of control surface oscillation. These results provide additional experimental verification of the existence of vortex wake instability predicated by theory and show that small oscillations in pitch at a critical frequency accelerate the dissipation of high-intensity vortices.

Chevalier, H.

"FLIGHT TEST STUDIES OF THE FORMATION AND DISSIPATION OF TRAILING VORTICES"

SAE Paper No. 73-0295, April 1973, Wichita, Kansas.

A flight test program has been conducted to measure experimentally parameters which describe the characteristics of vortex instability and behavior. Three basic atmospheric flight conditions were investigated: steady level flight in calm air, steady level flight in light gusting air and light winds, and

unsteady flight produced by control surface oscillations in calm air. A DeHavilland Beaver DHC-2 airplane and a Beechcraft T-34B airplane were used in the investigation. Smoke grenades were located near the wing tips of each airplane such that the vortices could be seeded with smoke and thus made visible. This made it possible to take measurements from photographs of the visible vortices. The experimental results show wavelengths of vortex instabilities, dissipation time of trailing vortices, effects of atmospheric current or gust, and the effect of control surface oscillation. These results provide additional experimental verification of the existence of vortex wake instability predicated by theory and show that small oscillations in pitch at a critical frequency accelerate the dissipation of high-intensity vortices.

Cheyne, E., Jokobsen, J. B., Snaebjornsson, J., Reuder, J., Kumer, V. and Svardal, B.

"ASSESSING THE POTENTIAL OF A COMMERCIAL PULSED LIDAR FOR WIND CHARACTERISATION AT A BRIDGE SITE"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 161, 2017, pp. 17-26.

Characterization of atmospheric turbulence is a central step prior to the construction of long-span bridges. The present paper investigates the potential of a long-range scanning pulsed coherent lidar to measure the wind field at the inlet of a fjord. The wind velocity data acquired by the lidar is compared to the data recorded by sonic anemometers installed on the bridge. The focus is on the ability of the lidar to capture single and two-point statistics of turbulence in complex terrains. Satisfying results are obtained with the Line-of-Sight scanning mode, which provides the best sampling frequency (1 Hz). The low temporal resolution and the low signal-to-noise ratio for the Range Height Indicator and the Plan Position Indicator scanning modes are important limiting factors in the pilot study performed. Better results may be achieved for a lidar measurement set-up which is adapted specifically for investigating coherence.

Chichka, D. F., Speyer, J. L., Fanti, C. and Park, C. G.

"PEAK-SEEKING CONTROL FOR DRAG REDUCTION IN FORMATION FLIGHT"

Journal of Guidance, Control, and Dynamics, Vol. 29, No. 5, September-October 2006, pp. 1221-1230.

Formation flight is a known method of improving the overall aerodynamic efficiency of a pair of aircraft. In particular, one craft flying in the correct position in the vortex wake of another can realize substantial reductions in drag, with the amount of the reduction dependent on the relative position of the two craft. This paper looks at such a pair, with one craft flying behind and to the side of the lead plane. The precise position of the second craft relative to the first to maximize the drag reduction is to be determined online, leading to a peak-seeking control problem. A new method of speak-seeking control, using a Kalman filter to estimate the characteristics of the drag reduction, is derived and discussed. A simple model of the two-plane formation using horseshoe vortices is defined, and the peak-seeking controller is applied to this model. The method is demonstrated using this simplified model.

Chigier, N. A.

"MEASUREMENT OF VORTEX BREAKDOWN OVER A DELTA WING USING A LASER ANEMOMETER"

NEAR TR-62, January 1974, Nielsen Engineering and Research Inc., Mountain View, CA

A preliminary experimental study has been made on vortex breakdown over and in the wake of a slender delta wing at low speed. The investigation was made in the NASA/Ames 7- by 10-Foot Wind Tunnel on a slender sharp-edged delta wing with aspect ratio of 1.56 and sweep angle of 70 deg. Smoke visualization showed the presence and structure of the vortex core and feeding sheet over the wing surface. Vortex breakdown occurred in the wake of the wing at an angle of attack of 20 deg. Photographs show a clear distinction between the core structure in the pre- and post-breakdown conditions. As the angle of attack was increased further to 35 deg., the location of vortex breakdown moved upstream over the wing surface. Secondary vortices could be clearly distinguished, formed at the trailing edge near the wing tips. Wind-tunnel balance measurements of lift and drag forces show reduction in lift and drag coefficients due to vortex breakdown for angles of attack above 20 deg. The NASA/Ames two-color laser Doppler velocimeter was used to measure streamwise and circumferential velocity distributions through the vortex centers at various planes over the wing surface and at a distance of half-chord downstream of the wing trailing edge.

Chigier, N. A.

"VORTEXES IN AIRCRAFT WAKES"

Scientific American, Vol. 230, No. 3, March 1974, pp. 76-83

The advent of the jumbo jets has turned the well-known aerodynamic phenomenon of trailing-vortex air turbulence into a potentially serious hazard to smaller following aircraft. The three main objectives of current research programs are reviewed: (1) ascertaining the nature, strength and persistence of the vortexes for various kinds of aircraft; (2) developing a practical means of reducing the hazard on existing aircraft by artificially inducing the vortexes to break up; and (3) setting up monitoring and control systems at airports to prevent aircraft from entering the vortex-wake turbulence of larger aircraft.

Chigier, N. A.

"EXPERIMENTAL STUDIES OF TURBULENT AIRCRAFT WAKES"

Israel Journal of Technology, Vol. 11, No. 6, December 1973, pp. 367-372

A review of wind tunnel test data obtained for tip vortex studies on a square-tipped rectangular wing. The results include wing surface pressure distributions, three-dimensional velocity components in the wake, and principal vortex characteristics such as peak tangential velocity and core size distribution. The wind tunnel measurements are compared with flight test data. These comparisons show that the

magnitudes of circumferential velocities, normalized by flight speed and lift coefficient, as well as the vortex core radius, normalized by wing span, are in close agreement. The data obtained make possible the calculation of turbulence stress distributions and the formulation of models for the prediction of downstream flow field.

Chigier, N. A.

"VELOCITY MEASUREMENT IN VORTEX FLOWS"

Flow: Its Measurement and Control in Science and Industry, Vol. 1, Part 1, edited by R. B. Dowdell, Instrument Society of America, 1974, pp. 399-408

Measurements have been made in swirling circular and annular free jets using five-hole pressure probes and a disk static pressure probe for determination of mean flow and static pressure fields. A 3-wire, hot wire anemometer probe has been used for measuring velocity components in wing tip trailing vortices. Turbulence measurements in recirculation zones of a swirl generator have been made by placing hot wire anemometers in six different orientations, plus or minus 45 degrees to each of the coordinate axes. Details of measuring systems and instruments are discussed and examples of measurements in vortex flows are presented.

Chigier, N. A. and Corsiglia, V. R.

"TIP VORTICES-VELOCITY DISTRIBUTIONS"

NASA TM X-62887, September 1971, NASA Ames Research Center, Moffett Field, CA

Detailed measurements of velocity distributions have been made in vortices generated at the tip of a square-tip, 18-inch-chord, 48-inch semispan blade mounted in the NASA-Ames 7-by 10-foot wind tunnel. Time-mean-average velocity components were measured using a triple-sensor hot wire probe operated by three separate anemometers. The dimensions of the vortex increase with distance downstream over the blade surface, and at $X/C=4$ the vortex core radius is 1.7% of the span.

Chigier, N. A. and Corsiglia, V. R.

"WIND TUNNEL TEST DATA FOR WING TRAILING VORTEX FLOW SURVEY"

NASA TM-X-62148, May 1972, NASA Ames Research Center, Moffett Field, CA

Data are presented on velocity measurements made with hot wire anemometers in the wake of a model of the CV-990 aircraft and a rectangular wing in the NASA-Ames 2.14x3.05 meter (7- by 10-foot) wind tunnel. Variables included angle of attack, tunnel speed and axial distance up to 12 chord lengths downstream from the wing trailing edge. Effects of deflecting trailing edge flaps and small spoiler panels are shown.

Chigier, N. A. and Corsiglia, V. R.

"WIND TUNNEL STUDIES OF WING WAKE TURBULENCE"

Journal of Aircraft, Vol. 9, No. 12, December 1972, pp. 820-825

Velocity measurements have been made in the wake of wings in the Ames 7- by 10-foot Wind Tunnel. Distributions of velocity components were measured with a three-wire anemometer up to 12 chord lengths downstream of a CV-990 aircraft model and a rectangular wing. Results show that increasing the drag increases the vortex core radius, reduces the maximum tangential velocities and increases the magnitude of axial velocity defects.

Childers, B. A. and Snow, W. L.

"VIDEO PHOTOGRAPHIC CONSIDERATIONS FOR MEASURING THE PROXIMITY OF A PROBE AIRCRAFT WITH A SMOKE SEEDED TRAILING VORTEX"

NASA TM-102691, June 1990, NASA Langley Research Center, Hampton, VA.

Considerations for acquiring and analyzing 30 Hz video frames for CCD cameras mounted in the wing tips of a Beech T-34 aircraft are described. Particular attention is given to the characterization and correction of optical distortions inherent in the data.

Chiu, Y. D. and Peters, D. A.

"NUMERICAL SOLUTIONS OF INDUCED VELOCITIES BY SEMI-INFINITE TIP VORTEX LINES"

J. Aircraft, Vol. 25, No. 8, August 1988, pp. 684-694

The method of Rand and Rosen (for improving convergence on computed axial induced velocity for a helical wake) is extended to include all velocity components, all points in the wake, and nonhelical vortex lines (contraction). The method is based on finding upper and lower bounds on the truncated integral. Comparisons with other methods show that the present approach is efficient and accurate. Further, it avoids the errors associated with discretization of the vortex lines. Convergence occurs in only three to five revolutions, about 10% of the normal requirement.

Chivae, H. S. and Sorensen, J. N.

"LARGE EDDY SIMULATION OF WIND TURBINE WAKES IN PRESCRIBED NEUTRAL AND NON-NEUTRAL ATMOSPHERIC BOUNDARY LAYERS"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012087-1 - 012087-8.

Large eddy simulation (LES) of an infinitely long wind farm in a fully developed flow is carried out based on solution of the incompressible Navier-Stokes equations. The wind turbines are modeled as

equivalent actuator disks by applying aerodynamic loads on the flow field using tabulated aerodynamic lift and drag coefficients to save computational time. As a substitute to standard wall modeling LES, a 'prescribed mean shear' profile (hereafter called PMS) approach has been implemented and analyzed for generating the desired turbulent shear flow. It is applied on Neutral, Stable and Convective atmospheric boundary layers in presence of the -actuator disc represented- wind turbines and qualitatively meaningful results of mean and fluctuating velocity field is obtained. The effect of four different sub-grid scale (SGS) models on the flow structure is investigated and it is seen that sub-grid scale modeling (in particular, the Mix-O and Smagorinsky models) improves the accuracy of the simulations. An optimal grid resolution is also proposed for this kind of simulation.

Chizhov, V. A. and Kuznetsov, O. A.

"PROBABILISTIC EVALUATION OF AIRPLANE DESTRUCTION AT ENCOUNTER WITH VORTEX WAKE"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 283-288

The paper addresses likelihood destruction of airplane at encounter with a vortex wake generated by a preceding airplane. The danger of flying through vortex wakes is compared with natural atmospheric hazards.

Cho, J., Jeong, S. and Yee, K.

"APPLICATION OF PROPER ORTHOGONAL DECOMPOSITION FOR AVIATION SAFETY"

ICAS-2016-0576, September 2016, Daejeon, Korea.

In this study, the proper orthogonal decomposition reduced order method using various basis weight estimation methods is examined for efficient prediction of wake vortices. The proper orthogonal decomposition cannot guarantee the accurate prediction for the variation of a meteorological condition, in this research introduces neural network as basis weight estimation method which can perceive the nonlinear relationship between the input variables and the reduced variables. The neural network is trained with pairs of design variables and reduced variables, which are obtained from snapshot data of the LES simulation of the wake turbulence. The constructed POD/NN is applied to wake turbulence prediction for validations, and its results are compared to those of the full order analysis (LES simulations). As a result, it is found that the POD/NN has the capability to predict behavior and dissipation of wake vortices accurately.

Choi, J.-K. and Chahine, G. L.

"NON-SPHERICAL BUBBLE BEHAVIOR IN VORTEX FLOW FIELDS"

Computational Mechanics, Vol. 32, Issue 4-6, December 2003, pp. 281-290.

The boundary element method is applied to solve the unsteady behavior of a bubble placed in a vortex flow field. The steady vortex field is given in terms of the viscous core radius and the circulation, both of which may vary along the vortex axis. For this study, 2DynaFS, an axisymmetric potential flow code which has been verified successfully for diverse type of fluid dynamic problems, is extended. The modifications to accommodate the ambient vortex flow field and to model the extreme deformations of the bubble are presented. Through the numerical simulations, the time history of the bubble geometry and the corresponding pressure signal at a fixed field point are obtained. A special effort is made to continue the numerical simulation after the bubble splits into two or more sub-bubbles. Indeed, it is found that an elongated bubble sometimes splits into smaller bubbles, which then collapse with the emission of strong pressure signals. The behavior of the axial jets after the split is also studied in more detail.

Choi, S.

"EXPERIMENTAL INVESTIGATION OF WING-TIP VORTEX EVOLUTION BEHIND A HALF-DELTA WING EQUIPPED NACA0012 WING"

Master of Engineering Thesis, 2015, McGill University, Montreal, Quebec, Canada.

The modification of the tip vortex, generated by a rectangular NACA0012 wing, was attempted using four different tip-mounted half-delta wing (HDW) models at a chord Reynolds number of 245,000. The HDW models used in this experiment were i) $\lambda = 65$ degrees, $c_{sub r} = 1c$, ii) $\lambda = 50$ degrees, $c_{sub r} = 1c$, iii) $\lambda = 50$ degrees, $c_{sub r} = 0.5c$ and iv) $\lambda = 50$ degrees, $c_{sub r} = 0.3c$ where c , $c_{sub r}$ and λ are baseline chord, root chord and slenderness, respectively. In addition to the cases listed above, the impact of the deflection was also investigated. Because of the vortex breakdown, the roll-up process of the tip vortex was found to be significantly modified. Especially, HDWs with the $c_{sub r}$ less than or equal to 50 percent exhibited a unique double-vortex pattern, one originating from the tip of the baseline wing and the other one from the leading-edge of the HDW. HDWs with the $c_{sub r}$ less than or equal to 50 percent also caused a rapid diffusion of vorticity and rendered a weak circulation flow-like tip vortex, suggesting an enhanced wake-vortex decay and alleviation. The interaction and merging of double-vortex were expedited by both increasing the angle of attack and deflecting the HWD upward. Regardless of the vortex breakdown, the lift of the HWDs was found to increase with the increasing angle of attack and stayed above the value of the baseline wing. The $c_{sub r} = 0.5c$ produced an improved lift-to-drag ratio.

Chomaz, J.-M., Donnadieu, C. and Ortiz, S.

"THREE-DIMENSIONAL INSTABILITIES AND TRANSIENT GROWTH OF TRAILING VORTICES IN HOMOGENEOUS AND STRATIFIED FLOWS"

AIAA Paper 2008-3800, Seattle, WA, June 2008

An aircraft wake is made up counter-rotating vortices and is known to be affected by a long (Crow) and a short (elliptic) wavelength instability. Numerical investigations on the three-dimensional and

transient growth of such dipole are performed. By means of a three-dimensional linear stability analysis, we retrieve the instability bands corresponding to the Crow and elliptic modes but we also observe less unstable oscillatory modes with very broad peaks. The transient growth of perturbations on this dipole, investigated by computing the optimal linear perturbations with a direct-adjoint technique, demonstrates the crucial role of the region of maximal strain at short time and of the hyperbolic point at intermediate time. Investigations on the three-dimensional dynamics of trailing vortices in stratified fluids are performed. The elliptic instability is almost unaffected by weak and moderate stratifications.

Chometon, F. and Laurent, J.

"STUDY ON THREE DIMENSIONAL SEPARATED FLOWS, RELATION BETWEEN INDUCED DRAG AND VORTEX DRAG"

European Journal of Mechanics, B/Fluids, Vol. 9, No. 5, 1990, pp. 437-45.

The origin of drag of high aspect ratio bodies is well known, and is usually split into two categories, profile drag and induced drag. For simple shapes, these quantities can be obtained through computation, and/or through measurements in wind tunnels. For low aspect ratio bodies like road vehicles such an analysis is not easy, and the idea of induced drag is replaced by the notion of vortex drag. The goal of this paper is to clarify vortex drag, particularly in comparison to induced drag as introduced by Prandtl. This is achieved by experimentation on a finite aspect ratio wing where these two types of drag can be more easily separated and quantified. Finally, an experimental method based on the lifting line theory is proposed for measurement of the induced drag of an airfoil through downstream velocity surveys.

Chon-Yin, T. and Widnall, S. E.

"THE STABILITY OF SHORT WAVES ON A STRAIGHT VORTEX FILAMENT IN A WEAK EXTERNALLY IMPOSED STRAIN FIELD"

J. Fluid Mech., Vol. 73, Pt. 4, February 1976, pp. 721-733

The stability of short-wave displacement perturbations on a vortex filament of constant vorticity in a weak externally imposed strain field is considered. The circular cross-section of the vortex filament in this straining flow field becomes elliptical. Instability of short waves on this strained vortex can occur only for wavelengths and frequencies at the intersection points of the dispersion curves for an isolated vortex. The vortex is unstable at wavelengths for which $\Omega = 0$, thus giving some support to the instability mechanism for the vortex ring proposed recently by Widnall et al., (1974). The growth rate is calculated by linear stability theory.

Chorin, A. J. and Bernard, P. S.

"DISCRETIZATION OF A VORTEX SHEET WITH AN EXAMPLE OF ROLL UP"

FM-72-5, November 1972, Univ. of California, Berkeley, CA

The point vortex approximation of a vortex sheet in two space dimensions is examined and a remedy for some of its shortcomings is suggested. The approximation is then applied to the study of the roll-up of a vortex sheet induced by an elliptically loaded wing.

Choroba, P.

"A VISION OF WAKE VORTEX RESEARCH FOR NEXT 20 YEARS"

Fifth EUROCONTROL/FAA ATM R&D Seminar, June 2003, Budapest, Hungary.

International regulations require commercial airliners to be separated in flight by up to six nautical miles (11.12 km) due to the potential hazard caused by the swirling air left in their wakes. This 'wake vortex' is now the subject of intense worldwide research to understand the nature of the phenomenon, to develop reliable technology for its detection and prediction and thus find ways of making air travel safer while reducing congestion around airports. This paper describes author's beliefs on current and future research in wake vortex domain in relation to survey research being currently conducted within his PhD thesis.

Choroba, P.

"COMPREHENSIVE STUDY OF THE WAKE VORTEX PHENOMENA TO THE ASSESSMENT OF ITS INCORPORATION TO ATM FOR SAFETY AND CAPACITY IMPROVEMENTS"

Ph.D. Thesis, 2006, University of Zilina, Slovak Republic

Wake turbulence is one of the main causes for airport capacity problems in air transportation. The lift force exerted on aircraft wings produces vortices with long life-times in their wake. Especially during an aircraft's critical landing phase vortices can endanger any aircraft trailing behind. Serious problems with wake vortices were first recognized back in the 1970s when the Boeing 747 came into service. Pilots of smaller aircraft who followed the much heavier B 747 in to landing reported suddenly strong turbulence that even caused some aircraft to crash. Safe separation distances (ICAO) are prescribed to ensure that an aircraft does not enter an unsafe situation due to the wake turbulence of a preceding aircraft. These separation distances have been defined in the past based on aircraft weight classes. Some modifications of these rules have been introduced by the regulating authorities that reflect the experience obtained over the years. Nevertheless, neither the original proposals nor these modified rules can always be explained by rigorous physically-based reasoning. It also resulted in a lack of harmonization between the various airports or authorities. It is felt that the regulations that prescribe the separation distances might be too conservative in most cases or too optimistic for very specific meteorological conditions. The overall objective of this thesis is the understanding of the nature of wake turbulence phenomena in Air Traffic Management (ATM) for potential safety and capacity improvements. Therefore, this study was defined in four main research axes: state-of-the-art of physics, technology and operational procedures, definition of users' (pilots and air traffic controllers) requirements by operational survey, estimation of capacity benefit through fast-time simulations and

safety analysis including probabilistic risk assessment of wake vortex safety. We also introduce a new concept of dynamic separations with transitions between two separation modes depending on the actual meteorological conditions, and within the safety analysis part of the thesis we propose a new conservative probabilistic model for wake vortex safety assessment.

Choroba, P. and Duong, V.

"THE CONCEPT OF INTEGRATED AIR TRAFFIC CONTROL WAKE VORTEX SAFETY AND CAPACITY SYSTEM"

IEEE Proceedings, Intelligent Transportation Systems, Vol. 1, October 2003, pp. 684-688

International regulations require commercial airliners to be separated in flight by up to six nautical miles (11.12 km) due to the potential hazard caused by the swirling air left in their wakes. This 'wake vortex' is now the subject of intense worldwide research to understand the nature of the phenomenon and find ways of making air travel safer while reducing congestion around airports. 'With the world airline fleet expected to double in size over the next 15 years and the giant A380 entering service in 2005, solutions to the wake-vortex problem cannot come too soon for the aerospace industry and therefore there is a strong need for developing a dynamic air traffic control wake vortex safety and capacity system.' This paper describes the concept of integrated transportation system regarding the current state-of-the-art technologies.

Chou, H. Y., Liu, Y. C. and Hsiao, F. B.

"THE AERODYNAMIC BEHAVIORAL STUDY OF TWO WING'S WAKE FLOW IN TANDEM ARRANGEMENT"

Procedia Engineering, Vol. 67, 2013, pp. 1-14.

This paper is aimed to study the aerodynamic properties and flow structures of flow field between two wings in tandem arrangement, including the experiments of force and velocity measurement in the wind tunnel. From the hot-wire velocity measurements, the spectral analysis is also conducted to observe the flow development of the trailing vortices. It is found that there is a sudden drop of shedding frequency distribution at the distance of 4 to 5 times the chord length from the front wing when AOA=10 degrees, which determines the distance between the front wing and following wing, and understand the dynamic response of following wing under the effect of trailing vortices from the front wing at constant angle of attacks. In addition, the aerodynamic performance of the following wing is drastically affected due to the impingement of the tip vortices or wake from the front wing as well.

Choudhry, A., Mo, J.-O., Arjomandi, M. and Kelso, R.

"EFFECTS OF WAKE INTERACTION ON DOWNSTREAM WIND TURBINES"

Wind Engineering, Vol. 38, No. 5, 2014, pp. 535-548.

The present article revisits the wake studies behind the NREL (National Renewable Energy Laboratory) Phase VI wind turbine inside a virtual wind tunnel that were recently performed at the University of

Adelaide using Large Eddy Simulation (LES). A notable observation has been made in the current article, through comparisons of instantaneous contours of vorticity, velocity, and turbulence intensity, that the regions of velocity deficits and high turbulence intensities in the wake are restricted to the region of high vorticity. Therefore, for a downstream wind turbine, the smaller power production, the increased unsteady loads and the noise produced can directly be associated with the turbine blades passing through the streamwise vortices generated by the upstream wind turbine. In addition, a comparative analysis has been performed between the LES and semi-empirical models, used in the industry, to better understand the development of the wake inside the wind tunnel model. Finally, to illustrate the effects of wake on downstream wind turbines, a dynamic stall prediction model was used to determine the regions of the turbine blade affected by dynamic stall as a function of spacing between the turbines.

Chow, C.-Y. and Huang, M.-K.

"UNSTEADY FLOWS ABOUT A JOUKOWSKI AIRFOIL IN THE PRESENCE OF MOVING VORTICES"

AIAA Paper No. 1983-0129, Reno, NV, January 1983

The motion of discrete vortices in the vicinity of a Joukowski airfoil and the influence of these vortices on airfoil lift and drag are computed using a computer code that has been written based on conformal mapping and unsteady flow analyses. With this computer code, studies are made on the stability of a trapped vortex when perturbed away from its equilibrium position with a finite displacement, on the release of a free vortex at a location upstream from an airfoil, and on the behavior of a moving vortex of increasing strength. Numerical results indicate that under proper arrangements free vortices can be utilized to generate high lift or thrust on an airfoil.

Chow, J. S.

"TURBULENCE MEASUREMENTS IN THE NEAR-FIELD OF A WINGTIP VORTEX"

PhD Thesis, August 1994, Stanford University, Palo Alto, CA.

The roll-up of a wingtip vortex, at Reynolds number based on chord of 4.6 million, was studied with an emphasis on suction side and near wake measurements. The research was conducted in a 32 in. x 48 in. low-speed wind tunnel. The half-wing model had a semi-span of 36 in., a chord of 48 in. and a rounded tip. Seven-hole pressure probe measurements of the velocity field surrounding the wingtip showed that a large axial velocity, of up to $1.77U$, developed in the vortex core. This level of axial velocity has not been previously measured. Triple-wire probes have been used to measure all components of the Reynolds stress tensor. It was determined from correlation measurements that meandering of the vortex was small and did not appreciably contribute to the turbulence measurements. The flow was found to be turbulent in the near-field (as high as 24 per cent RMS w-velocity on the edge of the core) and the turbulence decayed quickly with streamwise distance because of the nearly solid body rotation of the vortex core mean flow. A streamwise variation of the location of peak levels of turbulence, relative to the core centerline, was also found. Close to the trailing edge

of the wing, the peak shear stress levels were found at the edge of the vortex core, whereas in the most downstream wake planes they occurred at a radius roughly equal to one-third of the vortex core radius. The Reynolds shear stresses were not aligned with the mean strain rate, indicating that an isotropic-eddy-velocity based prediction method cannot accurately model the turbulence in the vortex. In cylindrical coordinates, with the origin at the vortex centerline, the radial normal stress was found to be larger than the circumferential.

Chow, J. S., Zilliac, G. G. and Bradshaw, P.

"MEAN AND TURBULENCE MEASUREMENTS IN THE NEAR FIELD OF A WINGTIP VORTEX"

AIAA Journal, Vol. 35, No. 10, October 1997, pp. 1561-1567

The rollup of a wingtip vortex, at a Reynolds number based on chord of 4,600,000, was studied with an emphasis on suction side and very near-wake measurements (up to $x/c = 0.678$ downstream of the trailing edge). The research was conducted in a 32 x 48 in. (0.81 x 1.22 m), low-speed wind tunnel. The rectangular half-wing model had a semispan of 36 in. (0.91 m), a chord of 48 in. (1.22 m), and a rounded tip. Seven-hole pressure probe measurements of the velocity field surrounding the wingtip showed that a large axial velocity, up to levels not previously measured, developed in the vortex core. Triple-wire probes were used to measure all components of the Reynolds stress tensor. It was determined from correlation measurements that meandering of the vortex was small and did not contribute appreciably to turbulence measurements. The flow was found to be turbulent in the near field (as high as 24% rms velocity), and the turbulence decayed quickly with streamwise distance because of the stabilizing effect of the nearly solid body rotation of the vortex-core mean flow. A streamwise variation of the location of peak levels of turbulence, relative to the core centerline, was also noted. Close to the trailing edge of the wing, peak shear stress levels were measured at the edge of the vortex core, whereas in the most downstream wake plane, the peak levels were measured at a radius roughly equal to one-third of the vortex core radius. The Reynolds shear stress (in Cartesian coordinates) was not aligned with the mean strain rate, indicating that an isotropic-eddy-viscosity-based prediction method cannot fully model the turbulence in the vortex. In cylindrical coordinates, with the origin at the vortex centerline, the radial normal stress was found to be larger than the circumferential component.

Chow, J. S., Zilliac, G. G. and Bradshaw, P.

"MEASUREMENTS IN THE NEAR-FIELD OF A TURBULENT WINGTIP VORTEX"

AIAA Paper No. 1993-0551, Reno, NV, January 1993

The roll-up of a wingtip vortex, at Reynold's numbers based on chord of 4.6 million, was studied with an emphasis on suction side and near wake measurements. The research was conducted in a 32 in. x 48 in. low-speed wind tunnel. The half-wing model had a semi-span of 36 in., chord of 48 in. and a rounded tip. Surface oil flow and laser smoke flow studies were conducted, showing the highly three-dimensional nature of the flow around the wingtip, the formation of the feeding sheet, and the viscous

core region of the vortex. Airfoil surface pressure measurements clearly showed a chordwise line of large suction under the primary vortex. Seven-hole pressure probe measurements of the velocity field surrounding the wingtip showed that a large axial velocity developed in the vortex core and is not currently being computed correctly by Navier Stokes codes. A 'kink' in the path of the vortex core was discovered slightly downstream of the trailing edge. Triple-wire probes have been used to measure all components of the Reynolds stress tensor. It was determined from flow visualization and correlation measurements that meandering of the vortex was small and did not appreciably contribute to the turbulence measurements. All the turbulent normal stress components recorded high levels in the vortex core. The contours of Reynolds shear stress differed in shape to those found by previous researchers on fully rolled-up vortices.

Chow, J. S., Zilliac, G. G. and Bradshaw, P.

"INITIAL ROLL-UP OF A WINGTIP VORTEX"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 35-1 - 35-17

The roll-up of a wingtip vortex, at high Reynolds number, was studied with an emphasis on suction side and near wake measurements. Research was conducted in the 32 in x 48 in low-speed wind tunnel at the Fluid Mechanics Laboratory of NASA Ames Research Center. The half-wing model has a 3-ft semispan and 4-ft chord, with a NACA 0012 airfoil section and rounded tip. Angle of attack of the wing was set at 10 degrees and the Reynolds number based upon chord was 4.6 million. Flow visualization studies using surface oil flow and laser smoke flow techniques were conducted, showing the highly three-dimensional nature of the flow around the wingtip and illuminating the formation of the feeding sheet and the viscous core region of the vortex. Airfoil surface pressure measurements, taken at over 450 locations on the upper and lower surface of the wing, clearly showed a suction peak associated with the development of the primary vortex. Seven-hole pressure probe measurements of the velocity field surrounding the wingtip showed an axial core velocity magnitude of approximately 1.7 times the freestream velocity. This level of axial velocity is not currently being computed correctly by Navier Stokes codes.

Chow, K. W.

"INVISCID SECONDARY INSTABILITY OF THE FAR WAKE"

Phys. Fluids A, Vol. 2, No. 7, July 1990, pp. 1149-1157

The three-dimensional (3-D) instability of a parallel mean flow and a two-dimensional (2-D) wave is examined. Such secondary instability is shown to exist for the Gaussian profile as a model for the wake. Numerical results are obtained based upon a recently proposed wave-mean-flow interaction mechanism, with the assumptions of temporal problem and inviscid flows. Classical 2-D instability is strong in the near wake but decays to zero in the far wake, where it is overwhelmed by 3-D instability.

It is conjectured that this will qualitatively explain the emergence of three-dimensionality in the far wake.

Chowdhury, H., Mustary, I., Loganathan, B. and Alam, F.

"ADJACENT WAKE EFFECT OF A VERTICAL AXIS WIND TURBINE"

Procedia Engineering, Vol. 105, 2015, pp. 692-697.

The main objective of this study is to understand the effect of turbine placement and surrounding structures. Using Urban Green Energy's UGE-4K vertical axis wind turbine and the ANSYS computational fluid dynamics package (CFX), a dynamic fluid analysis was undertaken looking at the wake of the turbine through a variety of different inlet speeds and rotational frequencies to determine suitable flow recovery for optimal placement of subsequent turbines. The results showed that the wake interference is minimal at around 5 times the diameter of the turbine downstream. Results also show that flow recovery was a lot slower to the right of the turbine especially along a line 15 degrees from the center of the turbine to the right as this is coincident with the vortices generated from the turbines rotation.

Christiansen, J. P.

"VORTEX: A 2-DIMENSIONAL HYDRODYNAMICS SIMULATION CODE"

CLM-R-106, July 1970, United Kingdom Atomic Energy Authority, Culham, England

Program VORTEX is a computer code which simulates the behavior of an incompressible, inviscid homogeneous fluid in two dimensions by following the motion of a large number of point vortices. The theory behind the program and the program itself are described.

Christiansen, J. P.

"NUMERICAL SIMULATION OF HYDRODYNAMICS BY THE METHOD OF POINT VORTICES"

Journal of Computational Physics, Vol. 135, 1997, pp. 189-197

The motion of a two-dimensional incompressible inviscid and homogeneous fluid can be thought of in terms of the gradual evolution of a continuous vorticity distribution, each scalar vortex element interacting with every other by an instantaneous action at a distance law. It is of particular interest that this model can be expressed in Hamiltonian form and that it shows many analogies with similar systems in plasma physics. In addition to the standard mesh techniques, a computational description can be obtained if the continuous vorticity distribution is replaced by a finite set of point vortices interacting through a stream function which satisfies Poisson's equation. The point vortices move in a velocity field given on a Cartesian mesh such that there is a close resemblance to particle models used in plasma simulations. The point vortex model is presented with a calculation on a test model and the sources of numerical errors are explained. Graphical results from several calculations are shown and it

is concluded that the point vortex model is useful and versatile for a variety of problems in hydrodynamics as well as in plasma physics.

Christien, R., Hoffman, E., Trzmiel, A. and Zeghal, K.

"AN EXTENDED ANALYSIS OF SEQUENCING ARRIVALS AT THREE MAJOR EUROPEAN AIRPORTS"

AIAA Paper 2018-3843, June 2018, Atlanta, GA.

This paper presents an analysis of the sequencing of arrival flights at three major European airports representative of different types of operation with more than 24000 aircraft pairs. The motivation is to better understand and characterize how sequencing is performed in dense and complex environments during peak periods. The analysis, purely data driven, focuses on the dynamic of spacing over time, investigating in particular, convergence and reactionary aspects. The two main results are: (1) progressive convergence of the spacing with a deviation up to ± 2.5 min at 10min to final, and ± 50 s at 5min to final; and (2) noticeable reactionary effect with a queue additional time up to 3min at 10min to final and 50s at 5min to final. These values may reflect the level of difficulty and sensitivity of sequencing during peak periods in such dense and complex environments. Future work will involve analyzing high and late reactionary situations, investigating how this approach may help identifying improvement areas, and assessing the impact of a change for future operations.

Chu, C.-C., Wang, C.-T., Chang, C.-C., Chang, R.-Y. and Chang, W.-T.

"HEAD-ON COLLISION OF TWO COAXIAL VORTEX RINGS: EXPERIMENT AND COMPUTATION"

Journal of Fluid Mechanics, Vol. 296, 1995, pp. 39-71.

Head-on collision of two coaxial vortex rings has been studied by joint experimental and numerical investigation. The Reynolds number, Re , based on the initial circulation of the vortex rings, ranged from 400 to 2700. Besides numerical data, the vorticity field was also resolved by a non-intrusive visualization technique, LIPA, which enabled simultaneous measurement of velocities at multiple locations on a plane area. It was found that the enstrophy, rather than circulation, revealed three stages of evolution of the vortex rings prior to their breakdown. These include the free-traveling stage, stage of vortex stretching and the stage of viscous dissipation dominance. The results indicate that it would be incorrect to neglect the viscous effect, in particular, for the latter two stages of flow development. In fact, the rebound behavior of the vortex rings for lower Re is essentially a viscous phenomenon and is found to be closely related to the dissipation of enstrophy when the vortex rings are brought to interact actively with each other and is also related to the increase of the vorticity core diameter in the stage of dominance of viscous dissipation. Furthermore, an instant dimensionless group, N/Re , based on the local vorticity distribution and the radius of a vortex ring, is found to be appropriate to characterize the onset of instability. Our investigation indicates that, in the range of observation, bulging instability will be observed during collision when N/Re exceeds a critical value which is a function of the initial core-size of the vortex ring. Comparisons showed that the numerical, measured, and visualization results were in consistent agreement; this not only enables us to assess the

range of validity of the axisymmetry assumed for the numerical simulation, but also provides us with a rational basis for further analysis of azimuthal instability.

Chung, K. H., Kim, J. W., Ryu, K. W., Lee, K. T. and Lee, D. J.

"SOUND GENERATION AND RADIATION FROM ROTOR TIP-VORTEX PAIRING PHENOMENON"

AIAA Journal, Vol. 44, No. 6, June 2006, pp. 1181-1187

Sound generation and radiation from rotor-tip-vortex pairing are calculated numerically. Wake geometries of a two-bladed rotor in axial flights are calculated using a time-marching free-wake method without a nonphysical model of the far wake. The acoustic field can be obtained using acoustic analogy. To show the accuracy of the flow calculation scheme, the tip-vortex geometries of the present calculation are compared with those done in the previous publication of a small-scaled rotor experiment. The accuracy of the vortex sound calculation scheme is validated by comparing its numerical and the analytic solution of circular vortex-ring interaction. The tip-vortex pairing consists of a turn of the tip-vortex from one blade rolling around the tip-vortex from the other blade. The tip-vortex pairing amplifies the noise and generates new dominant frequencies. The tip-vortex pairing noise has a quadrupole directivity pattern, and it is especially dominant in the direction of the rotation axis. The peak components of the noise spectrum represent the pairing period and an instability mode.

Chung, K. H., Kim, J. W., Ryu, K. W., Lee, K. T. and Lee, D. J.

"SOUND GENERATION AND RADIATION FROM ROTOR TIP-VORTEX PAIRING PHENOMENON"

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Churchfield, M. J. and Blaisdell, G. A.

"NEAR FIELD WINGTIP VORTEX COMPUTATION USING THE WIND CODE"

AIAA Paper No. 2006-633, Reno, NV, January 2006

The accuracy of current state-of-the-art turbulence models and a compressible Reynolds-averaged Navier-Stokes (RANS) solver in simulating the formation of wingtip vortices in the near field is investigated. The RANS solver used for this investigation is NPARC's WIND 5.0 code. Turbulence models explored are the standard Spalart-Allmaras model, the Spalart-Allmaras model with correction for system rotation and streamline curvature, and Menter's Shear Stress Transport model. Effect of grid resolutions and order of accuracy of numerical schemes are explored. Computational results are compared with the data of a reliable and thorough experiment. A comparison of these cases shows clear gains in accuracy when the flow field is computed using the rotation corrected Spalart-Allmaras turbulence model and a fifth-order numerical scheme on a computation grid of 4.5 million points. Both mean and turbulence quantities are studied.

Churchfield, M. J. and Blaisdell, G. A.

"A REYNOLDS STRESS RELAXATION TURBULENCE MODEL APPLIED TO A WINGTIP VORTEX FLOW"

AIAA Paper 2011-0663, January 2011, Orlando, FL.

A Reynolds stress relaxation model, specifically Olsen and Coakley's lag Reynolds stress transport (RST) model, is applied to a wingtip vortex flow, and its performance is assessed and compared with other aerospace standard turbulence models. A Reynolds stress relaxation model allows for Reynolds stress history effects due to streamline curvature, which are seen to play an important role in the non-diffusive nature of turbulent vortices. This study shows that the lag RST turbulence model is capable of predicting mean flow results as accurate as those of the well-performing Spalart-Allmaras model with correction for streamline curvature and system rotation (SA-RC). Furthermore, in this wingtip vortex flow, the lag RST model predicts turbulence quantities more accurately than the SA-RC model. Although the lag RST model performs well in predicting this flow, it has some deficiencies such as an inability to independently control the Reynolds stress magnitude and relaxation amount.

Churchfield, M. J. and Blaisdell, G. A.

"REYNOLDS STRESS RELAXATION TURBULENCE MODELING APPLIED TO A WINGTIP VORTEX FLOW"

AIAA Journal, Vol. 51, No. 11, November 2013, pp. 2643-2655.

A Reynolds stress relaxation model, specifically the lag Reynolds stress transport model, is applied to a wingtip vortex flow, and its performance is assessed and compared with other aerospace standard turbulence models. A Reynolds stress relaxation model allows for Reynolds stress history effects due to streamline curvature, which are seen to play an important role in the nondiffusive nature of turbulent vortices. This study shows that the lag Reynolds stress transport turbulence model can predict mean flow results as accurately as those of the well-performing Spalart-Allmaras model with correction for streamline curvature and system rotation. Furthermore, in this wingtip vortex flow, the lag Reynolds stress transport model predicts turbulence quantities more accurately than the rotation/curvature-corrected Spalart-Allmaras model. Although the Reynolds stress transport model well predicts this flow, it is more computationally intensive to solve than the rotation/curvature-corrected Spalart-

Allmaras model, and it has some deficiencies, such as an instability to independently control the Reynolds stress magnitude and relaxation moment.

Churchfield, M. J. and Blaisdell, G. A.

"NUMERICAL SIMULATIONS OF A WINGTIP VORTEX IN THE NEAR FIELD"

J. Aircraft, Vol. 46, No. 1, Jan.-Feb. 2009, pp. 230-243

We investigate the accuracy of current state-of-the-art turbulence models and a compressible Reynolds-averaged Navier-Stokes solver in computing the formation of a wingtip vortex in the near field. The Reynolds-averaged Navier-Stokes solvers used in this investigation are the NPARC WIND 5.0 and WIND-US 1.0 codes. The turbulence models explored are the standard Spalart-Allmaras model, the Spalart-Alimaras model with correction for system rotation and streamline curvature, the Menter shear stress transport model, and the Rumsey-Gatski explicit algebraic stress model. Additionally, we study how solution accuracy is affected by using higher-order numerical schemes as opposed to more grid points. Accuracy is assessed by comparing the results of the wingtip-vortex computations with the data of a reliable, thorough experiment. The solutions obtained using a fifth-order-accurate numerical scheme show that the Spalart-Alimaras turbulence model with corrections for rotation and streamline curvature predicts the mean flow most accurately. However, we find that within the vortex, none of the turbulence models explored accurately captures the magnitudes of the turbulence quantities or the lag of the Reynolds stress components behind the corresponding strain-rate components.

Ciffone, D. L.

"CORRELATION FOR ESTIMATING VORTEX ROTATIONAL VELOCITY DOWNSTREAM DEPENDENCE"

Journal of Aircraft, Vol. 11, No. 11, November 1974, pp. 716-717

The wake velocity profile was examined up to 200 span lengths in a water tank, and comparisons were made of measured and predicted maximum tangential velocities downstream. Two characteristic flow regions were identified. First, a 'plateau' region with little if any change in maximum tangential velocity downstream as great as 100 span lengths. This is followed by a decay region in which the maximum tangential velocity decreases with downstream distance at a rate nominally proportional to the inverse one-half power.

Ciffone, D. L.

"VORTEX INTERACTIONS IN MULTIPLE VORTEX WAKES BEHIND AIRCRAFT"

Journal of Aircraft, Vol. 14, No. 5, May 1977, pp. 440-446

A flow visualization technique has been developed that allows the nature of lift-generated wakes behind aircraft models to be investigated. The technique is applicable to models being towed underwater in a ship model basin. Several different configurations of a 0.61-m (2-ft) span model of a

Boeing 747-type transport aircraft were tested to allow observation of typical vortex interactions and merging in multiple vortex wakes. The vortices were identified by emitting tracer dyes from selected locations on the model. Their trajectories were obtained from photographs of the wake. Wingspan loading and model attitude were found to effect both vortex motions within the wake and resulting far-field wake velocity. Landing-gear deployment caused a far-field reformation of vorticity behind a model configuration which dissipated concentrated vorticity in the near-field wake. Circulation from the wing always caused a downward movement of the horizontal tail vortices, which merged with wing vortices. A modified landing configuration was developed that appeared to significantly alleviate the concentrated wake vorticity associated with the current landing configuration.

Ciffone, D. L.

"MEASUREMENTS OF AIRCRAFT WAKE ALLEVIATION AND GROUND PLANE EFFECTS"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 173-182

In support of the NASA wake vortex alleviation program, vortex trajectories and velocity profiles were measured in lift-generated wakes. The wakes were generated by towing 0.61-m (2-ft) span models of B-747 and DC-10-30 aircraft under water in a ship model basin. The effects of flaps, spoilers, and ground plane on these wakes were investigated. A laser velocimeter was used to measure vertical (tangential) velocity profiles through primary vortices from 5- to 100-wingspan lengths behind the generating model. A 45° deflection of the two outboard flight spoilers on the B-747 model in the landing configuration resulted in a 40% reduction in wake maximum tangential velocity, in altered velocity profiles, and in erratic vortex trajectories. Similar reductions in maximum tangential velocity were obtained for this model when the outboard flaps were retracted. Presence of a ground plane used to simulate full-scale distances above the ground of 38 m (125 ft) and 21 m (70 ft) modified the vortex trajectories but did not appreciably change vortex interactions and merging. However, at 21 m above the ground plane, the alleviation appeared to be enhanced due to vortex viscous interactions with the ground plane.

Ciffone, D. L. and Lonzo, C.

"FLOW VISUALIZATION OF VORTEX INTERACTIONS IN MULTIPLE VORTEX WAKES BEHIND AIRCRAFT"

NASA TM X-62459, June 1975, NASA Ames Research Center, Moffett Field, CA. (Also, AIAA Paper 76-62.)

A flow visualization technique has been developed which allows the nature of lift-generated wakes behind aircraft models to be investigated. The technique has been applied to models being towed underwater in a ship model basin. Seven different configurations of a small-scale model of a 747 transport aircraft were used to allow observation of typical vortex interactions and merging in multiple vortex wakes. It was established that the motion of the wake vortices is often sensitive to small changes in either wing span loading or model attitude. Landing gear deployment was found to cause a

far-field reformation of vorticity behind a model configuration which dissipated concentrated vorticity in the near-field wake. Alleviation of wake vorticity is achievable by configuring the wing span loading to cause the wake vortices to move in paths that result in their interactions and merging.

Ciffone, D. L. and Orloff, K. L.

"AXIAL FLOW MEASUREMENTS IN TRAILING VORTICES"

AIAA Journal, Vol. 12, No. 8, August 1974, pp. 1154-1155

A scanning laser Doppler velocimeter was used to measure the axial velocity defect in the cores of trailing vortices behind a lifting airfoil of rectangular planform. Data were obtained at several different angles of attack and downstream distances ranging from 30 to 103 chord lengths.

Ciffone, D. L. and Orloff, K. L.

"FAR-FIELD WAKE-VORTEX CHARACTERISTICS OF WINGS"

Journal of Aircraft, Vol. 12, No. 5, May 1975, pp. 464-470

Velocity measurements have been made in the wake of wings that were being towed underwater. As the wake aged, measurements of the tangential and axial velocity profiles were made with a two-dimensional scanning laser velocimeter at downstream distances of 5 to 200 span lengths behind wings with different span loadings. The results identify two characteristic flow regions for the dependence of vortex maximum tangential velocity on downstream distance. The first, a region with little, if any change in maximum tangential velocity, extends from wake rollup to downstream distances as great as 100 span lengths, depending on span loading and angle of attack. This is followed by a decay region in which the maximum tangential velocity decreases with downstream distance at rates nominally proportional to the inverse one-half power. It is shown that tailoring the wingspan loading by either planform or flap deflection can reduce the maximum vortex tangential velocity by a factor of 2 and thus broaden the vortex core. Vortex mutual interactions and instabilities were introduced by alternate up-down flap deflections, delaying vortex rollup to downstream distance of 45 spans.

Ciffone, D. L. and Orloff, K. L.

"APPLICATION OF LASER VELOCIMETRY TO AIRCRAFT WAKE-VORTEX MEASUREMENTS"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 157-192,

The theory and use of a laser velocimeter that makes simultaneous measurements of vertical and longitudinal velocities while rapidly scanning a flow field laterally are described, and its direct application to trailing wake-vortex research is discussed. Pertinent measurements of aircraft wake-vortex velocity distributions obtained in a wind tunnel and water towing tank are presented. The utility of the velocimeter to quantitatively assess differences in wake velocity distributions due to wake dissipating devices and span loading changes on the wake-generating model is also demonstrated.

Ciffone, D. L. and Pedley, B.

"MEASURED WAKE-VORTEX CHARACTERISTICS OF AIRCRAFT IN GROUND EFFECT"

AIAA Paper 1978-0109, January 1978, Huntsville, AL.

In support of the NASA wake vortex alleviation program, measurements were made of the influences of a ground plane on vortex trajectories and velocity profiles within lift-generated wakes. The wakes were generated by towing 0.61-m (2-ft) span models of a B-747 and DC-10-30 under water in a ship model basin. The models were configured with landing flaps and flight spoilers to investigate the wake characteristics of these aircraft in ground effect at simulated full-scale distances of 19 m (62 ft) to 116 m (380 ft) above the ground. The ground plane caused modifications in the vortex trajectories but did not alter vortex interactions and merging patterns in these multiple vortex wakes. Some distortions in vortex vertical (tangential) velocity profiles were recorded because of vortex lateral motions and vortex interactions with the viscous boundary layer on the ground plane; however, maximum tangential velocities remained unchanged.

Ciffone, D. L. and Pedley, B.

"MEASURED WAKE-VORTEX CHARACTERISTICS OF AIRCRAFT IN GROUND EFFECT"

Journal of Aircraft, Vol. 16, No. 2, February 1979, pp. 102-109

In support of the NASA wake vortex alleviation program, measurements were made of the influences of a ground plane on vortex trajectories and velocity profiles within lift-generated wakes. The wakes were generated by towing 0.61-m span models of a B-747 and DC-10-30 under water in a ship model basin. The models were configured with landing flaps and flight spoilers to investigate the wake characteristics of these aircraft in ground effect at simulated full-scale distances of 19-116 m above the ground. The ground plane caused modifications in the vortex trajectories but did not alter vortex interactions and merging patterns in these multiple vortex wakes. Some distortions in vortex vertical (tangential) velocity profiles were recorded as a result of vortex lateral motions and vortex interactions with the viscous boundary layer on the ground plane; however, maximum tangential velocities remained unchanged.

Ciffone, D. L., Orloff, K. L. and Grant, G. R.

"LASER DOPPLER VELOCIMETER INVESTIGATION OF TRAILING VORTICES BEHIND A SEMI-SPAN SWEPT WING IN A LANDING CONFIGURATION"

NASA TM-X-62294, August 1973, NASA Ames Research Center, Moffett Field, CA

Measured axial and tangential velocity profiles in the near wake vortices of a semi-span model of the Convair 990 wing in the NASA-Ames 7- by 10-foot wind tunnel are presented. A scanning laser Doppler velocimeter was used to obtain data at two different downstream stations (0.49 and 1.25 wing spans)

at various angles of attack and configurations from wing alone to wing plus nacelles, anti-shock bodies, and flaps deflected 27 deg (landing configuration). It is shown that the velocity distributions within the wake are quite sensitive to span loading. Specifically, it is illustrated that an aircraft flying at given lift coefficient, can substantially reduce its trailing vortex upset potential by deploying its flaps and altering its flight attitude to maintain the same lift coefficient. This might be taken into consideration along with performance and noise considerations in the selection of aircraft approach lift over drag.

Clark, D. R. and Landgrebe, A. J.

"WAKE AND BOUNDARY LAYER EFFECTS IN HELICOPTER ROTOR AERODYNAMICS"

AIAA Paper No. 1971-0581, Palo Alto, CA, June 1971

Theoretical methods recently developed within United Aircraft are discussed in light of the new understanding they give to the aerodynamics of the helicopter rotor. Results of wake geometry prediction methods, supported by experimental data, emphasize the importance of wake effects on rotor performance and behavior. These effects are shown to be especially important in hover and low speed forward flight as well as for high-speed flight at low disc angles. The influence of viscosity has been studied with particular emphasis on the development of the blade boundary layer. Using two independent boundary layer calculation methods, centrifugal pumping has been shown to play only a minor role with Coriolis forces and streamline curvature effects predominating. Away from separation and in the absence of large crossflows or excessive streamline curvature the boundary layer flow appears to be essentially two dimensional when taken in the direction of the external stream.

Clark, I. O.

"LIDAR AND ELECTRO-OPTICS FOR ATMOSPHERIC HAZARD SENSING AND MITIGATION"

AIAA Paper 2012-2788, June 2012, New Orleans, Louisiana.

This paper provides an overview of the research and development efforts of the Lidar and Electro-Optics element of NASA's Aviation Safety Program. This element is seeking to improve the understanding of the atmospheric environments encountered by aviation and to provide enhanced situation awareness for atmospheric hazards. The improved understanding of atmospheric conditions is specifically to develop sensor signatures for atmospheric hazards. The current emphasis is on kinetic air hazards such as turbulence, aircraft wake vortices, mountain rotors, and windshear. Additional efforts are underway to identify and quantify the hazards arising from multi-phase atmospheric conditions including liquid and solid hydrometeors and volcanic ash. When the multi-phase conditions act as obscurants that result in reduced visual awareness, the element seeks to mitigate the hazards associated with these diminished visual environments. The overall purpose of these efforts is to enable safety improvements for air transport class and business jet class aircraft as the transition to the Next Generation Air Transportation System occurs.

Clark, K. L., Wassaf, H. S., Wang, F. Y., Gulsrud, A. and Dunkel, J.

"WAKE VORTEX ACOUSTIC CHARACTERISTICS AND SOCRATES SENSOR PERFORMANCE"

DOT-VNTSC-NASA-07-01, July 2007, Volpe National Transportation Systems Center, Cambridge, MA

This report provides an evaluation of the current state of the SOCRATES sensor and its readiness for use as an operational sensor for active monitoring of aircraft wake turbulence. SOCRATES is a laser opto-acoustic array designed to passively detect and track the sound emissions of aircraft vortices. The evaluation period, January 2003 to December 2006, included two field tests designed to improve understanding of the fundamentals of wake acoustic phenomenology and aspects of the SOCRATES sensor performance.

Clark, M.

"WAKE TURBULENCE - GONE WITH THE WIND"

Journal of Traffic Control, Vol. 19, October-December 1977, pp. 10-12

In May 1976 a Vortex Advisory System (VAS) was installed at Chicago's O'Hare airport. The VAS is based on wind measurements around the airport which make it possible to predict movement and behavior of aircraft generated wake vortices. The VAS installation includes a network of meteorological towers sited near the middle marker locations. The wind data from the anemometers on the towers are transmitted to a central computer. The computer transmits through a digital display to the controller advising whether he can use reduced (3 n mi) separations in place of standard separation between arriving aircraft. NASA has been engaged in an extensive research program for the aerodynamic alleviation of wake vortices. Aerodynamic alleviation is a general term describing modifications to the aircraft or airfoil to alter the vortex structure and thereby minimize the adverse effects of the wake.

Clark, T. L. and Radke, L. F.

"LITTLE KNOWN FORMS OF INVISIBLE TURBULENCE MAY PRESENT SEVERE CHALLENGE TO PILOTS"

ICAO Journal, Vol. 56, No. 7, September 2001, pp. 5-7, 28

Recent research using observations and computer modelling has helped improve our understanding of the nature of clear air turbulence. The next step in studying phenomena such as vortex tubes is to extend modelling efforts to yet finer resolutions.

Clawson, K. L.

"VORTEX CIRCULATION VALUES FROM HOT FILM ANEMOMETER-MEASURED VORTEX VELOCITY PROFILES"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 83-89

Vortex circulation has been used to indicate vortex strength, but circulation cannot be directly determined from hot film anemometers. This paper describes several vortex circulation calculation methods that were developed and evaluated using the 1990 Idaho Falls hot film anemometer velocity profile data from B-727, B-757, and B-767 aircraft. Visual inspection of graphs of relative circulation as a function of vortex age showed vortex strength to be a clear function of aircraft model. The smallest relative circulation values were observed for the B-727, while the B-767 exhibited largest values at increasing vortex age. Although the highest tangential velocities were recorded for the B-757, this aircraft fits as expected into its weight category when the velocity values are converted to circulation values.

Clawson, K. L.

"NOAA METEOROLOGICAL DATA SUMMARY (LEVEL 2 DATA)"

Wake Vortex Research Data Package No. NOAA-2, December 1990, Environmental Research Laboratories, Idaho Falls, ID.

This document contains the Level 2 processed meteorological data collected by the National Oceanic and Atmospheric Administration (NOAA) during the 1990 spring and fall field vortex measurement periods at the NOAA test facility near Idaho Falls, Idaho. It updates the previously issued data packet NOAA-1 which describes the test site, the type and amount of meteorological data collected, and includes various data tables. This packet does not duplicate the information found in NOAA-1, but does provide updated data tables and graphs of the data. Two different types of data were collected during the measurement periods. The data are comprised of (1) tower data, and (2) tethered balloon data. The tower data consists of air temperatures, wind speeds, and wind directions measured concurrently at heights of 6.25, 12.5, 25, 50, 100, 150, and 200 feet above ground level. Each instrument was scanned every second. The data reported here are Level 2 three-minute averages obtained prior to the time the aircraft was abeam of the tower. The tethered balloon data consists of air temperatures, humidity, wind speeds, and wind directions measured at various heights up to approximately 1000 feet above ground level. The actual height of each measurement was determined by pressure relationships. Hence, the height of each measurement was not constant from sounding to sounding.

Clees, S., Lewalle, J., Frederick, M. and O'Connor, J.

"VORTEX CORE DYNAMICS IN A SWIRLING JET NEAR VORTEX BREAKDOWN"

AIAA Paper 2018-0052, January 2018, Kissimmee, FL.

The dynamics of the vortex core are investigated in a swirling jet at swirl numbers in the range of the critical swirl number for vortex breakdown. Vortex breakdown, a bifurcation in the structure of a swirling jet, results in the establishment of a stagnation point and recirculation region along the centerline of the jet. In this study, we explore the dynamics of the swirling jet near vortex breakdown.

Investigation of time-averaged velocity fields and profiles leads to the identification of three flow regimes: pre-breakdown, near-breakdown, and post-breakdown. Velocity fields in these regimes are further analyzed using dynamic mode decomposition, Rankine-vortex fitting, and proper orthogonal decomposition to characterize jet dynamics with a particular focus on the development of the recirculation region characteristic of vortex breakdown. A precessing vortex core is also identified in the post-breakdown regime and its behavior is discussed.

Clements, R. R. and Maull, D. J.

"THE ROLLING UP OF A TRAILING VORTEX SHEET"

Aeronautical Journal, Vol. 77, No. 745, January 1973, pp. 46-51

The investigation is oriented towards finding circulation distributions which alter the rolling up characteristics of the sheet in such a way as to retard the rolling up and decrease the vorticity finally contained in such rolled up vortex cores. Because the aircraft concerned have, typically, aspect ratios of about 7 and lift coefficients of about 1.0, the Westwater model was used.

Clifford, S. F., Kaimal, J. C., Lataitis, R. J. and Strauch, R. G.

"GROUND-BASED REMOTE PROFILING IN ATMOSPHERIC STUDIES: AN OVERVIEW"

Proceedings of the IEEE, Vol. 82, No. 3, March 1994, pp. 313-355.

Over the last 25 years, ground-based profiling has found increasing applications in atmospheric studies where its high vertical and temporal resolution and extended vertical coverage are giving scientists a clearer understanding of atmospheric processes in the troposphere. In this paper we describe the status of techniques for vertical profiling of mean wind speeds, temperature, and humidity, and discuss options for combining them.

Clive, P. J. M., Dimwoodie, I. and Quail, F.

"DIRECT MEASUREMENT OF WIND TURBINE WAKES USING REMOTE SENSING"

European Wind Energy Association (EWEA) 2011, March 2011, Brussels, Belgium.

Understanding wind turbine wakes is vitally important in both the onshore and offshore wind power context, and during both the development phase and post-construction. The accuracy of the wake models used during the development phase of a wind power project to evaluate the losses and loads arising from wind turbine wakes has historically been assessed with references to power output at operational wind farms under a variety of waked conditions. This method of assessment however introduces some ambiguity due to the assumptions that must be made about the status of the wind power assets themselves and the influence this has on the power which is being used fundamentally as a proxy of free stream wind speed. A more satisfactory approach is to deploy remote sensing devices such as Lidar to measure the flow field under waked conditions directly. This presentation will review

the use of Lidar devices with fully steerable beams and long ranges (about 4km) sufficient to perform the sorts of wide area detailed and precise surveys of the wind flow through large arrays of wind turbines to investigate the formation, propagation and interaction of wind turbine wakes with each other and wind power assets. In essence there are many occasions where wind turbines themselves have been employed as large expensive anemometers for the assessment of wake models. This assessment can be more properly conducted using the remote sensing techniques now available which are reviewed in this presentation.

Cochran, L., Peterka, J. and Petersen, R.

"PHYSICAL MODELLING OF ROOF-TOP HELICOPTER EXHAUST FLOW DISPERSION"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 83, 1999, pp. 347-360.

A technique for physically modelling the interaction of helicopter rotor flows with the natural wind in a boundary-layer wind tunnel is described. This technique is used to measure the dilution of helicopter exhaust fumes at the roof-level air intakes near the heliports on top of the new American Stores Company Headquarters building in Salt Lake City, Utah. The dilution values may then be compared to odor and health threshold limits in the literature. Physical modelling of the interaction of the helicopter rotor downwash and the ambient wind around a complex architectural roof shape was used to determine the suitability of the locations chosen for the building air intakes. This approach is appropriate where any heliport operation interacts with the HVAC system of an office building or hospital.

Cocle, R., Dufresne, L. and Winckelmans, G.

"INVESTIGATION OF MULTISCALE SUBGRID MODELS FOR LES OF INSTABILITIES AND TURBULENCE IN WAKE VORTEX SYSTEMS"

Lecture Notes in Computational Science and Engineering, Vol. 56, 2007, pp. 141-159.

This paper investigates the capabilities of different sub-grid scale (SGS) models, including the recent 'multiscale' models, for large-eddy simulation (LES), here in a vortex-in-cell method, of complex wake vortex dynamics. More specifically, we here consider the multiscale dynamics developing in a counter-rotating four-vortex system, that evolves from a simple state to a turbulent state. The various SGS models are tested and compared on this complex and transitional flow. Comparisons are also made with results obtained using a pseudo-spectral method. Energy diagnostics (global and modal) and spectra are provided and used to support the comparisons. A discussion on the applicability of the various models to LES of complex wake vortex flows is made. The multiscale models are seen to be the most appropriate.

Cohen, B. and Smith, A.

"IMPLEMENTATION OF A LOW-COST SSR/ADS-B AIRCRAFT RECEIVER DECODER"

Proceedings of the 17th AIAA/IEEE/SAE Digital Avionics Systems Conference, Bellevue, WA, October-November 1998. Institute of Electrical and Electronics Engineers, Inc., 1998, Vol. 2, pp. F44-1 - F44-8

A real-time stand-alone radar receiver decoder system has been developed and implemented. The system decodes all radar data on the 1090- and 1030-MHz downlink and uplink, including Mode S, TCAS, ATCRBS, ADS-B, and IFF. In a typical terminal area, the system decodes real-time aircraft radar data at up to 10 Hz from each aircraft. This paper describes the application of the system to assist with several ATC research programs, including wake vortex research. The equipment set up and integration with a wake vortex sensor suite are described, and results are presented from field trials at JFK International Airport.

Cohen, D.

"A METHOD FOR DETERMINING THE CAMBER AND TWIST OF A SURFACE TO SUPPORT A GIVEN DISTRIBUTION OF LIFT"

NACA TN-855, August 1942, Langley Aeronautical Lab., Langley Field, VA

A graphical method is described for finding the shape (camber and twist) of an airfoil having an arbitrary distribution of lift. The method consists in replacing the lifting surface and its wake with an equivalent arrangement of vortices and in finding the associated vertical velocities. By a division of the vortex pattern into circular strips concentric about the downwash point instead of into the usual rectangular strips, the lifting surface is reduced for each downwash point to an equivalent loaded line for which the induced velocity is readily computed. The ratio of the vertical velocity to the stream velocity is the slope of the surface in the free-stream direction. As an illustration, the shape of the wing consistent with the pressure distribution derived from the two-dimensional theories is found for two wings: a straight elliptical wing and one with 30-degree sweepback. Application of the method to solve the reverse problem - finding the lift distribution over a given surface - is briefly discussed.

Cohen, S., editor

"CONCEPT PAPER FOR SEPARATION SAFETY MODELING: AN FAA/EUROCONTROL COOPERATIVE EFFORT ON AIR TRAFFIC MODELING FOR SEPARATION STANDARDS"

Concept Paper, FAA/Eurocontrol, May 1998

In today's air traffic environment, there is an emphasis on economic, cost-efficient operations and the need to not just maintain aviation safety, but dramatically improve it. With this emphasis has come the requirement to modernize en-route and terminal air traffic operations. This is being accomplished by transitioning to satellite-based navigation and surveillance, the equipage of ground facilities and aircraft cockpits with new technology, and the introduction of new airspace procedures and rules. Both the FAA and EUROCONTROL face this challenge of airspace modernization. An overriding concern of both organizations is that as the modernization occurs, aviation safety is maintained and improved. This paper describes the beginnings of an attempt to create a model for the use in airspace where radar separation is provided, one that will enable the estimation of the risk of a midair collision or other

safety problem (e.g., serious wake vortex encounter) as a function of parameters such as separation minima, accuracy of position information, integrity of systems, and controller automation aids.

Cohn, R. K. and Koochesfahani, M. M.

"EFFECT OF BOUNDARY CONDITIONS ON AXIAL FLOW IN A CONCENTRATED VORTEX CORE"

Physics of Fluids, Vol. A5, No. 1, January 1993, pp. 280-282.

The character of axial flow in the core of a concentrated line vortex is studied using flow visualization. Results show that axial flow can be initiated when the no-slip boundary condition is imposed on the vortex core over a spatial extent comparable to the core diameter. It is further demonstrated that no-slip is not a necessary condition to generate the axial flow; a region of spanwise shear (i.e., a slip boundary) is sufficient. Two distinct axial flow velocity profiles are observed; they are either jet-like or spatially undulated corresponding to a maximum axial speed occurring at the core center or outer edge, respectively.

Coimbra, R. F. F. and Catalano, F. M.

"THE EFFECT OF WING TIP BLOWING ON THE VORTEX DRAG"

ICAS-2002-3.10.2, Toronto, Canada, September 2002

Experimental work has been conducted to evaluate the effect of wing tip blowing on the vortex drag of a rectangular low aspect wing at low speed. A novel tip blowing system is presented which consist of three Coanda type jets. The jets can be vectored to produce a better tip vortex attenuation. Wind tunnel tests were performed for measurements of Lift, Drag and Pitching moment for many combinations of jet vertical angles and position. The tests were conducted at constant Reynolds number for incidence angles from -4 to 22 degrees. Results indicated an increase in Lift and pitching moment with an inherent decrease in drag for most of the configurations tested.

Coiro, D. P., Nicolosi, F., Scherillo, F. and Maisto, U.

"SINGLE VERSUS MULTIPLE WINGLETS: NUMERICAL AND EXPERIMENTAL INVESTIGATION"

ICAS Paper 2008-2.7.3, September 2008, Anchorage, Alaska.

The main goal of the paper is the numerical and experimental investigation of multiple winglets influence on the reduction of induced drag. This results in the improvement of climbing performances of a motor-glider or hang-glider. In a precedent work a set of multiple winglets, very similar to the bird tip feathers called remiges, were designed and optimized for the hang-glider belonging to Angelo D'Arrigo, a world champion hang-glider pilot and record holder. The research aims were to optimize the endurance parameter since this is directly proportional to the sink rate. In this work the effects of the multiple winglets, set on an elliptical wing and tested in a wind tunnel, are compared to the effects of three different single 'classical' winglets that were designed using a panel method code and were also

tested in the same wind tunnel in order to compare their span efficiency to the one of the multiple winglets.

Cole, J. A., Maughmer, M. D., Bramesfeld, G. and Kinzel, M.

"A PRACTICAL APPLICATION OF AN UNSTEADY FORMULATION OF THE KUTTA-JOUKOWSKI THEOREM"

AIAA Paper 2017-3904, June 2017, Denver, CO.

In this paper, a practical application of the unsteady Kutta-Joukowski theorem to a higher-order potential flow method is developed and discussed. The formulation of the unsteady version of the Kutta-Joukowski theorem is compared with a pressure integration on a flat plate to assess the origins of the non-circulatory term. The approach is varied through comparison with classical unsteady thin-airfoil solutions for the lift response to a sharp-edged gust a sinusoidal gust. Finally, the approach is used to predict the unsteady lift response of a propeller-wing system and the results are compared with a fully unsteady Reynolds-Averaged Navier Stokes analysis.

Cole, R.

"WIND PREDICTION TO SUPPORT REDUCED AIRCRAFT WAKE VORTEX SEPARATION STANDARDS"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

Air traffic delays were a major problem in the US prior to September 11, 2001, and are expected to climb to record levels in the near future. Wake vortex separation standards are an important contributor to the delay problem. Wake vortices are narrow diameter vortices generated as a function of aircraft lift that trail behind an aircraft generating a potential hazard to following aircraft. In certain circumstances, inter-aircraft spacing is increased to alleviate this hazard. The current aircraft separation standards are formulated to keep aircraft safe in the worst-case situation, and do not consider the fact the vortices may have blown out of the way or may have decayed due to atmospheric turbulence. When wake vortex separations are applied, spacing between aircraft is increased from a minimum of 2.5 nm to 4-6 nm (depending on the weight of the following aircraft), decreasing the number of operations per hour below demand at busy airports. The initial work in developing algorithms to predict when surface crosswinds will stay strong enough to ensure that wake vortex separations can safely be removed from behind the downwind aircraft departing from closely spaced parallel runways is discussed, along with some ideas on extending the initial work to improve reliability and forecast lead time. The work to date focuses on using anemometer data. A proof-of-concept study evaluated the applicability of the surface crosswind prediction algorithm used in the Frankfurt wake prediction system and a new candidate statistical prediction algorithm at four USA airports. This was followed by a study to extend the new surface crosswind prediction algorithm to use the Low Level Windshear Alert System network of anemometers at the St. Louis airport, so that predictions can be provided for a broader area. Statistical techniques to predict surface crosswinds in the airport region with long enough

prediction horizons to apply to departure operations have been shown to perform with a significant level of skill.

Cole, R. E. and Winkler, S.

"WIND PREDICTION TO SUPPORT REDUCED WAKE SEPARATION STANDARDS FOR CLOSELY SPACED PARALLEL RUNWAY DEPARTURES"

Proceedings of the 11th Conference on Aviation, Range, and Aerospace Meteorology, Hyannis, MA, 2004.

The FAA is considering the issue of how to reduce the use of wake avoidance separation for closely spaced parallel runway departures (runways separated by less than 2500 ft.). The ability to safely remove the wake avoidance separation requires the ability to predict when the crosswind will stay above some, yet unspecified, threshold level. There is a candidate surface wind prediction algorithm in a prototype system operating at Frankfurt. This led the FAA to pose the question: Is there enough to surface wind prediction based on anemometer measurements to warrant further investigation? To answer this question the Frankfurt algorithm was examined, as well as a new algorithm developed at MIT Lincoln Laboratory. The results show that the number of prediction failures (type 1 errors) is low enough, possibly as low as a few tens of minutes per year, and the possible benefits high enough, 30-60% of the time wake avoidance separation can be removed, that further development is warranted. These results are based on data from a single point at the airport. Before this technology can be used in an operational system the results must be extended to cover the entire airspace where the departing aircraft remain separated laterally by less than 2500 ft.

Cole, R. E., Dennen, A. P. and Matthews, M. P.

"THE AVOSS WINDS ANALYSIS SYSTEM"

NASA/L-5, February 2001, MIT Lincoln Laboratory, Lexington, MA

Due to wake turbulence, aircraft operating in the terminal area must maintain minimum separations on instrument approaches. This can be a significant constraint on the airport arrival rate. NASA's Aircraft Vortex Spacing System (AVOSS) project was undertaken to develop the technology to dynamically change aircraft arrival separations based upon atmospheric conditions and an understanding of vortex behavior. As part of this effort, a collection of meteorological sensor systems were deployed by Lincoln Laboratory and NASA at the Dallas/Fort Worth International Airport (DFW). These sensors, along with existing FAA and NWS systems, are used to create profiles of the atmosphere at the DFW airport. Scientific concept prototypes of the AVOSS were operated at Dallas/FT. Worth in the summer of 1997-2000. The greatest challenge in preparing a single atmospheric profile for the wake vortex behavior models is merging data from sensors yielding different measurements of the same atmosphere. To meet this challenge, the AVOSS Winds Analysis System (AWAS) was developed to perform the data quality editing and fusion of sensor data.

Coleman, C. P.

"A SURVEY OF THEORETICAL AND EXPERIMENTAL COAXIAL ROTOR AERODYNAMIC RESEARCH"

NASA Technical Paper TP-3675, March 1997, Ames Research Center, Moffett Field, CA.

The recent appearance of the Kamov Ka-50 helicopter and the application of coaxial rotors to unmanned aerial vehicles have renewed international interest in the coaxial rotor configuration. This report addresses the aerodynamic issues peculiar to coaxial rotors by surveying American, Russian, Japanese, British, and German research. (Herein, 'coaxial rotors' refers to helicopter, not propeller, rotors. The intermeshing rotor system was not investigated.) Issues addressed are separation distance, load sharing between rotors, wake structure, solidity effects, swirl recovery, and the effects of having no tail rotor. A general summary of the coaxial rotor configuration explores the configuration's advantages and applications.

Coleman, G. N., Johnstone, R., Yorke, C. P. and Castro, I. P.

"DNS OF AIRCRAFT WAKE VORTICES: THE EFFECT OF STABLE STRATIFICATION ON THE DEVELOPMENT OF THE CROW INSTABILITY"

Direct and Large-Eddy Simulation VII, Vol. 13, Part 7, 2010, pp. 505-511.

A numerical experiment is performed to determine the likelihood that the Crow instability will mitigate the potentially hazardous effects of the buoyancy-induced rebound of initially parallel line vortices. Parameters are chosen to correspond to wake vortices downstream of an elliptically loaded wing with large span (typical of the A380) landing in very stable conditions. The DNS is initiated by perturbing the vortex pair into the shape of the linearly most unstable Crow eigenmode, with a maximum displacement of 1 percent of the initial distance between the pair. Under these conditions, the Crow instability progresses fast enough to break the two dimensionality of the vortex system before it returns to its original elevation. This suggests that in many cases the Crow instability will prevent the rebounding vorticity from being a danger to following aircraft. Whether or not this will always happen in practice is an open question, requiring further investigation.

Collar, A. R.

"ON THE ACCURACY OF THE REPRESENTATION OF A LIFTING LINE BY A FINITE SET OF HORSESHOE VORTICES"

The Aeronautical Quarterly, Vol. 9, Issue 3, August 1958, pp. 232-250.

The paper examines the error involved when the continuous distribution of lift on an unswept lifting surface is represented by a finite number of horseshoe vortices, the strengths of which are determined by a prescribed downwash. Attention is directed mainly to the case of elliptic loading, but an anti-symmetrical case is also studied to ensure that the conclusions are not peculiar to the elliptic case. Sensitivity analyses on the loading were examined for prescribing the downwash at the center of each

horseshoe vortex equal to that for the continuous case, as well as if circulation is determined for a wing of finite aspect ratio by its geometric incidence.

Collins, R. L.

"WAKE TURBULENCE MYSTERY"

Flying, Vol. 121, No. 7, July 1994, pp. 52-56

The 757's wake seems to be more powerful than those of similar-sized airplanes. But its takeoff and approach capability are what adds the unexpected dimension.

Colmer, M. J.

"SOME FULL-SCALE MEASUREMENTS OF THE FLOW IN THE WAKE OF A HANGAR"

C. P. No. 1166, November 1970, Royal Aircraft Establishment, Bedford, UK.

An experiment to measure the flow behind a full-scale building at RAE Bedford is described. The results of one set of data show that the whole wake was slowly oscillating and that the turbulence intensity in the wake was greater than upstream. An hypothesis for the wake motion is put forward and the effect of the wake behind a building on conventional V/STOL aircraft is considered.

Colonius, T., Lele, S. and Moin, P.

"SCATTERING OF SOUND WAVES BY A VORTEX: NUMERICAL SIMULATIONS AND ANALYTICAL SOLUTIONS"

J. Fluid Mech., Vol. 260, February 1994, pp. 271-298

The scattering of plane sound waves by a vortex is investigated by solving the compressible Navier-Stokes equations numerically, and analytically with asymptotic expansions. Numerical errors associated with discretization and boundary conditions are made small by using high-order accurate spatial differentiation and time marching schemes along with accurate non-reflecting boundary conditions. The accuracy of computations of flow fields with acoustic waves of amplitude five orders of magnitude smaller than the hydrodynamic fluctuations is directly verified. The properties of the scattered field are examined in detail. The results reveal inadequacies in previous vortex scattering theories when the circulation of the vortex is non-zero and refraction by the slowly decaying vortex flow field is important. Approximate analytical solutions that account for the refraction effect are developed and found to be in good agreement with the computations and experiments.

Colonius, T., Lele, S. K. and Moin, P.

"THE FREE COMPRESSIBLE VISCOUS VORTEX"

Journal of Fluid Mechanics, Vol. 230, 1991, pp. 45-73.

The effects of compressibility on free (unsteady) viscous heat-conducting vortices are investigated. Analytical solutions are found in the limit of large, but finite, Reynolds number, and small, but finite, Mach number. The analysis shows that the spreading of the vortex causes a radial flow. This flow is given by the solution of an ordinary differential equation (valid for any Mach number), which gives the dependence of the radial velocity on the tangential velocity, density, and temperature profiles of the vortex; estimates of the radial velocity found by solving this equation are found to be in good agreement with numerical solutions of the full equations. The experiments of Mandella also report a radial flow in the vortex, but their estimates are much larger than the analytical predictions, and it is found that the flow inferred from the experiments violates the Second Law of Thermodynamics for two-dimensional axisymmetric flow. It is speculated that three-dimensionality is the cause of this discrepancy. To obtain detailed analytical solutions, the equations for the viscous evolution are expanded in powers of Mach number, M . Solutions valid to order M^2 , are discussed for vortices with finite circulation. Two specific initial conditions - vortices with initially uniform entropy and with initially uniform density - are analyzed in detail. It is shown that swirling axisymmetric compressible flows generate negative radial velocities far from the vortex core owing to viscous effects, regardless of the initial distributions of vorticity, density and entropy.

Colonus, T., Lele, S. K. and Moin, P.

"SCATTERING OF SOUND WAVES BY A COMPRESSIBLE VORTEX"

AIAA Paper No. 91-0494, Reno, NV, January 1991

Scattering of plane sound waves by a compressible vortex is investigated by direct computation of the 2-d Navier-Stokes equations. Non-reflecting boundary conditions are utilized, and their accuracy is established by comparing results on different sized domains. Scattered waves are directly measured from the computations. The resulting amplitude and directivity pattern of the scattered waves is discussed, and compared to various theoretical predictions. For compact vortices (zero circulation), the scattered waves directly computed are in good agreement with predictions based on an acoustic analogy. Strong scattering at about plus or minus 30 degrees from the direction of incident wave propagation is observed. Back scattering is an order of magnitude smaller than forward scattering. For vortices with finite circulation refraction of the sound by the mean flow field outside the vortex core is found to be important in determining the amplitude and directivity of the scattered wave field.

Combe, H., Kopp, F. and Keane, M.

"ON-BOARD WAKE VORTEX DETECTION"

Presentation at the Third Wake-Net Workshop, Great Malvern, England, May 22-23, 2000

After collection of user requirements for airborne detection of wake-vortices and other atmospheric hazards, a future equipment has been defined and a demonstrator has been built. The demonstrator has been installed at the extremity of a runway on Toulouse airport so as to enable measurements in a

configuration very close to an on-board detection from a follower aircraft. This 'airborne-like' detection has been successful. The tracking method as well as the signal processing constitutes a world premiere that has demonstrated the feasibility of an airborne equipment. Industrial equipment for detection, warning and avoidance of wake-vortex, windshear and other atmospheric hazards could be brought to market within 5 to 8 years. To achieve this goal, it is important to progress in the system integration of the MFLAME concept. This global approach should be the subject of further work with two major objectives: (1) On board system integration with study of detection, warning and avoidance aspects, including avoidance maneuver trials in a flight simulator and flight tests; and (2) ATC and ground system integration, considering links with board system, to finally demonstrate how the operational capacity and safety of aircraft can be improved.

Condit, P. M.

"RESULTS OF THE BOEING COMPANY WAKE TURBULENCE TEST PROGRAM"

FAA Compilation of Working Papers Concerning Wake Turbulence Tests, April 1970

The results of a flight test investigation of vortex wake turbulence generated by large jet transport aircraft are presented. Test results showing the dynamic response of aircraft which were flown in the wakes of large jet transports, are discussed. Experimental results are compared to theoretical predictions. Test program results are applied to the problem of air traffic control and specific recommendations are presented for air traffic separations.

Condit, P. M.

"SUMMARY OF PANEL STATEMENT REGARDING WAKE TURBULENCE"

FAA Symposium on Turbulence, Federal Aviation Administration, Washington, DC, March 1971, p. 20

The Boeing Wake Turbulence Test Program is presented; the goal was to provide a comparison between the 747 wake and the wake of a smaller jet transport and to provide insight into the factors which are important when defining the hazards associated with wake turbulence. A B-737 and a CV-990 were flown behind a B-747 and a B-707. Little differences in the responses of the encountering aircraft were observed. It was concluded that: (1) the relative size of the generating and encountering airplanes is important and (2) the span ratio is the best parameter for defining 'hazard'.

Condit, P. M. and Tracy, P. W.

"RESULTS OF THE BOEING COMPANY WAKE TURBULENCE TEST PROGRAM"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 473-508

The Boeing Company initiated a study of large jet aircraft wake turbulence in mid-1969. The Boeing flight test program was undertaken to evaluate the behavior of trailing vortices and to obtain a direct comparison between the turbulent wakes of the 747 and a 707-320C. A fully instrumented Boeing 737-

100 was used as the primary wake probing aircraft. Additional probes were made with the Boeing owned F-86 and NASA's CV-990. It was found that the dynamic response of the chase airplanes was essentially the same when flying in the turbulent wakes of either the 747 or 707. It was observed that the wake leveled off and never descended more than 900 feet below the generating airplane. In the approach and landing tests it was found that the wake generated in ground effect does not 'roll up' into strong trailing vortices.

Cone Jr, C. D.

"THE THEORY OF INDUCED LIFT AND MINIMUM INDUCED DRAG OF NONPLANAR LIFTING SYSTEMS"

NASA TR R-139, 1962, Langley Research Center, Hampton, VA.

The basic theory of the induced lift and drag of nonplanar, circulation lifting systems is developed, and methods are evolved for determining the span force loading intensity necessary for minimum induced drag. It is shown that the aerodynamic efficiency of such optimally loaded systems can be expressed in terms of an effective aspect ratio which depends in value upon the spatial distribution of the vorticity of the system. Methods for determining the maximum effective aspect ratio of arbitrary lifting systems of given span by use of conformal transformation and electrical potential-flow analog techniques are developed and illustrated. The value of the induced-drag efficiency factor is determined for the families of circular, semi-ellipse, and complete-ellipse area and for several more complex forms. The result of the theory are interpreted in terms of the physical airfoil requirements necessary for successful realization of the theoretical induced-drag reductions. The practical application aspects of nonplanar wing systems are briefly considered.

Cone, Jr., C. D.

"A THEORETICAL INVESTIGATION OF VORTEX-SHEET DEFORMATION BEHIND A HIGHLY LOADED WING AND ITS EFFECT ON LIFT"

NASA TN-657, April 1961, Langley Research Center, Langley Field, VA

The induced drag polar is developed for wings capable of attaining extremely high loadings while possessing an elliptical distribution of circulation. This development is accomplished through a theoretical investigation of the vortex-wake deformation process and the deduction of the airfoil forces from the impulse and kinetic energy contents of the ultimate wake form. The investigation shows that the induced velocities of the wake limit the maximum lift coefficient to a value of 1.94 times the wing aspect ratio, for aspect ratios equal to or less than 6.5, and that the section properties of the airfoil limit the lift coefficient to 12.6 for aspect ratios greater than 6.5. Relations are developed for the rate of deformation of the vortex wake. It is also shown that linear wing theory is applicable up to lift coefficients equal to 1.1 times the aspect ratio.

Conlisk, A. T.

"MODERN HELICOPTER ROTOR AERODYNAMICS"

Progress in Aerospace Sciences, Vol. 37, Issue 5, July 2001, pp. 419-476.

The helicopter rotor wake is among the most complex fluid dynamic structures being three dimensional and, in many cases, unsteady. The wake begins at the blade(s) where the flow can be transonic near the blade tip and undergo compressible dynamic stall. Farther down in the wake, the flow is essentially incompressible. Moreover, the rotor blades undergo complex unsteady motions because of the necessity to balance moments; they are elastic as well. In this paper, the fundamental aeromechanics of the wake and the flow on the blade is discussed and the primary methods of analysis, computation, and experiment employed to uncover the physics of the rotor wake are described.

Conlisk, A. T.

"A THEORY OF VORTEX-SURFACE COLLISIONS"

AIAA Paper 1998-2858, June 1998, Albuquerque, NM.

The interaction of vortices with solid surfaces occurs in many different situations including, but not limited to tornadoes, propeller wakes, flows over swept wings and missile forebodies, turbomachinery flows, blade-vortex interactions and tip vortex-surface interactions on helicopters. Often, parts of a system must operate within such flows and thus encounter these vortices. In the present paper we discuss the nature of a particular subset of interactions called 'collisions'. A 'collision' is characterized by the fact that the core of the vortex is permanently altered; usually the core is locally destroyed. The focus is on fully three-dimensional collisions although two-dimensional collisions are discussed as well. Examples of collisions in helicopter aerodynamics and turbomachinery flows are discussed and the dynamics of the vortex core during a collision process are illustrated for a 90-degree collision.

Conlisk, A. T.

"MODERN HELICOPTER AERODYNAMICS"

Annual Review of Fluid Mechanics, Vol. 29, Ann. Rev. Inc., Palo Alto, CA, 1997, pp. 515-567.

Modern helicopter aerodynamics is challenging because the flow field generated by a helicopter is extremely complicated and difficult to measure, model, and predict; moreover, experiments and computational techniques have been employed to predict performance parameters. Of particular interest is the structure of the rotor wake, which is highly three-dimensional and unsteady, and the rotor-blade pressure distribution, which is significantly affected by the strength and position of the wake. We describe the various modern methods of computation and experiment which span the range from vortex techniques to full three-dimensional Navier-Stokes computations, and from classical probe methods to laser velocimetry techniques. Typical results for the structure of the wake and the blade pressure distribution in both hover and forward flight are presented despite the complexity of the

helicopter flow, significant progress has been made within the last ten years and the future will likely bring marked advances.

Conlisk, A. T. and Komerath, N. M.

"VORTEX SURFACE COLLISIONS"

ARO 30707.4-EG, March 1998, Ohio State University Research Foundation, Columbus, OH.

Many flows of practical interest contain discrete vortices. These include tornadoes, propeller wakes, and flows over swept wings and missile forebodies. The encounter of a vortex with a solid body is always a complex event involving very large gradients of pressure and velocity. We consider the problem in which a rotor-tip vortex collides with a helicopter airframe. The primary objective of this work is to describe both experimentally and computationally the interaction when the vortex 'collides' directly with the airframe in the sense that at some point the flow in the vortex core must be altered to accommodate the presence of the airframe. The pressure field caused by the collision is also described. The dominant physics of the collision process may be described by inviscid flow theory and it is the component directed along the tip-vortex axis, termed the axial flow, which is the major cause of the collision.

Conlisk, A. T. and Komerath, N. M.

"THE ORIGIN AND STRUCTURE OF TRAILING VORTICES IN AERODYNAMICS"

School of Aerospace Engineering, Report 733920, March 2001, Ohio State Univ., Columbus, OH

The helicopter rotor wake is among the most complex flow-fields in aerodynamics. Even though a large amount of computational and experimental work on the rotor wake has been published, little of a quantitative nature is known about the origin of the main component of the rotor wake, the tip-vortex, as a function of the rotor speed, rotor blade geometry and angle of attack. The primary objective of this work is to predict the formation of the rotor tip vortex as a function of physical parameters such as angle of attack, rotor speed, and blade aspect ratio. While the rotor-blade tip-vortex is of primary interest, the techniques developed are applicable to fixed wings as well.

Conlisk, A. T. and Veley, D.

"THE GENERATION OF NOISE IN IMPINGING VORTEX MOTION PAST A STEP"

Physics of Fluids, Vol. 28, No. 10, October 1985, pp. 3004-3012.

The noise field generated by the motion of one, two, or several rectilinear vortices in an inviscid, irrotational mean flow past a step is considered for low Mach number. The streak-line patterns of an impinging vortex are compared with flow visualization studies, and qualitative agreement between the present analytical results and the experiments is achieved. Both acoustic pressure and intensity are strong functions of the vortex motion near the step which, because of the complexity of the geometry,

must be computed numerically. Results for the acoustic pressure and intensity are presented for a variety of incident vortex arrays.

Conlisk, A. T., Li, H., Mei, N. and Budic, J.

"VORTEX-VORTEX INTERACTIONS IN THE WAKES OF THREE AND FOUR BLADED ROTORS"

American Physical Society, Fluid Dynamics Meeting, Nov. 1999, New Orleans, LA.

In recent experiments on a two-bladed rotor in low axial climb it was observed that vortices shed from each of the blades interacted significantly at approximately one rotor radius below the rotor disk plane. This phenomenon was verified by numerical solutions of the rotor wake for the same experimental conditions. In this paper we consider the case of three and four blades in hover. A lifting line is used to model each blade and a fully unsteady computation of the motion of each tip-vortex is carried out using a highly accurate Adams-Moulton method to advance the vortices. The vortex-vortex interaction is particularly complicated and several vortices are observed to become locally intertwined. It is suggested that this kind of behavior can be explained on the basis of classical vortex dynamics. Conditions under which the motion of the vortices is steady are also examined.

Conner, D. W. and Jacobson, I. D.

"PASSENGER RIDE COMFORT TECHNOLOGY FOR TRANSPORT AIRCRAFT SITUATIONS"

TM X-73953, October 1976, NASA Langley Research Center, Hampton, VA.

A brief overview is given of NASA research in ride comfort and of the resultant technology. Three useful relations derived from the technology are presented together with five applications of these relations to illustrate their effectiveness in addressing various ride comfort situations of passenger transports.

Connolly, S. T. and Dagle, W. R.

"THE MEASUREMENT OF WAKE VORTICES WITH A CLEAR-AIR DOPPLER RADAR"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 38-1 - 38-11

A Doppler radar system is currently under development by Applied Technologies and the U.S. Army to measure wind velocity and turbulence and to detect the atmospheric boundary layer height. For this type of radar high resolution is of prime concern since the top of the atmospheric boundary layer is characterized by small-scale turbulence which can be overlooked by instruments with coarser resolution. Because of the features designed into the radar to accomplish these tasks, a radar of this type may be feasible for operational airport monitoring of aircraft wake vortices to determine if wake vortex separation constraints may be relaxed. The all-weather ability of this radar may be used to determine the influence of weather on the persistence and decay of wake turbulence and to assess the

hazard presented by weather-reduced strength vortices. Applied Technologies has applied the technologies of pulsed radar wind profiles to duplicate the results of earlier work done with the FM-CW radars. This radar has been designed for continuous, unattended meteorological monitoring by including sophisticated signal processing, built in test equipment, and remote communications. This paper discusses the design features of this radar and how they could be applied to wake vortex detection and monitoring.

Connor, A. B. and O'Bryan, T. C.

"A BRIEF EVALUATION OF HELICOPTER WAKE AS A POTENTIAL OPERATIONAL HAZARD TO AIRCRAFT"

NASA TN D-1227, March 1962, NASA Langley Research Center, Langley AFB, VA

Flight tests with a single-rotor helicopter and a fixed-wing airplane are reported which show that helicopter wake presents a potential hazard to aircraft operating near the wake, particularly with regard to airport traffic situations. Operating practices suggested for reducing this hazard potential include reminding pilots of aircraft following a helicopter to remain above the helicopter flight path and, if in doubt about relative positions, to extend the separation interval between aircraft. An exact time interval was not determined, but a separation estimated to be about 1 minute appears to be a reasonable time with most of the present generation helicopters.

Consiglio, M., Chamberlain, J., Munoz, C. and Hoffler, K.

"CONCEPT OF INTEGRATION FOR UAS OPERATIONS IN THE NAS"

ICAS Paper 2012-10.7.1, September 2012, Brisbane, Australia.

One of the major challenges facing the integration of Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) is the lack of an onboard pilot that can comply with the legal requirement identified in the US Code of Federal Regulations that pilots see and avoid other aircraft. UAS will be expected to demonstrate the means to perform the function of see and avoid while preserving the safety level of the airspace and the efficiency of the air traffic system. This paper introduces a Sense and Avoid concept for integration of UAS into the NAS that is currently being developed by NASA and identifies areas that require additional experimental evaluation to further inform various elements of the concept. The concept design rests on interoperability principles that take into account both the Air Traffic Control environment as well as existing systems such as the Traffic Alert and Collision Avoidance System (TCAS). Specifically, the concept addresses the determination of well clear values that are large enough to avoid issuance of TCAS corrective Resolution Advisories, undue concern by pilots of proximate aircraft and issuance of controller traffic alerts. The concept also addresses appropriate declaration times for projected losses of well clear conditions and maneuvers to regain well clear separation.

Constant, G. D. J., Foord, R., Forrester, P. A. and Vaughan, J. M.

"THE DETECTION OF AIRCRAFT WAKE VORTICES BY LASER DOPPLER SIGNATURES: AN OLD PROBLEM REVISITED"

Optical Society of America, Technical Digest, Vol. 12, 1991, pp. 309-311.

Measurements made, using a compact laser Doppler velocimeter, of the wake vortices produced by aircraft landing at Heathrow Airport will be reported.

Constant, G., Foord, R., Forrester, P. A. and Vaughan, J. M.

"COHERENT LASER RADAR AND THE PROBLEM OF AIRCRAFT WAKE VORTICES"

Journal of Modern Optics, Vol. 41, No. 11, 1994, pp. 2153-2173

Aircraft wake vortices have been studied with a 10.6-micron coherent c.w. lidar. Good agreement is found between the form of experimentally observed Doppler spectra and theoretical calculations and modelling. Detailed measurements of spectra have yielded core radii, tangent velocities and vortex velocity profiles which are in reasonable accord with theoretical formulations. During a two-week trial, over 130 aircraft passages were recorded with the lidar equipment. Even in low signal to noise conditions vortex spectra were recorded on most occasions at a level above expectation. The characteristic cusp-like features of such spectral records are illustrated with a novel color display.

Constant, G., Foord, R., Forrester, P. A. and Vaughan, J. M.

"COHERENT LASER-RADAR AND THE PROBLEM OF AIRCRAFT WAKE VORTICES"

J. Modern Optics, Vol. 41, No. 11, November 1994, pp. 2153-2173

Aircraft wake vortices have been studied with a 10.6-micron coherent cw lidar. Good agreement is found between the form of experimentally observed Doppler spectra and theoretical calculations and modelling. Detailed measurements of spectra have yielded core radii, tangent velocities and vortex velocity profiles which are in reasonable accord with theoretical formulations. During a two-week trial over 130 aircraft passages were recorded with the lidar equipment. Even in low signal to noise conditions vortex spectra were recorded on most occasions at a level above expectation. The characteristic cusp-like features of such spectral records are illustrated with a novel color display.

Conti, R. J., Hoshizaki, H., Redler, K. O. and Cassady, P. E.

"ATMOSPHERIC DISPERSION OF AIRCRAFT EXHAUST"

AIAA Paper No. 1973-0100, January 1973, Washington, DC.

A model for the dispersal of exhaust from high-flying aircraft is proposed. This model was developed as part of a study to predict stratospheric pollution from supersonic transports and other aircraft that may be operating by 1990. The model addresses the exhaust trail from the engines to the point at

which aircraft-induced effects become negligible compared with natural atmospheric transport. This may involve lengths of trail on the order of 100 km. The model was developed from simple theoretical arguments and a study of condensation trails from jet aircraft.

Conway, R., Matuck, G. N., Roe, J. M., Taylor, J. and Turner, A.

"VORTEX INFORMATION DISPLAY SYSTEM PROGRAM DESCRIPTION MANUAL - DATA ACQUISITION FROM LASER DOPPLER VELOCIMETERS AND REAL TIME OPERATION"

NASA CR-120703, February 1975, M&S Computing, Huntsville, AL

A vortex information display system is described which provides flexible control through system user interaction for collecting wing-tip-trailing vortex data, processing this data in real time, displaying the processed data, storing raw data on magnetic tape, and post processing the raw data. The data is received from two asynchronous laser Doppler velocimeters and includes position, velocity, and intensity information. Both raw data and processing can be continually upgraded during flyby testing to improve vortex behavior studies.

Copening, G. and Anderson, J.

"NUMERICAL SOLUTIONS TO THREE-DIMENSIONAL SHOCK WAVE/VORTEX INTERACTION AT HYPERSONIC SPEEDS"

AIAA Paper No. 1989-0674, January 1989, Reno, NV.

An upwind difference, finite volume algorithm was used to numerically solve the full three-dimensional Euler equations for two flow fields, Mach numbers 2.28 and 5.00, each containing a helical-type vortex impinging on an oblique shock wave. These solutions showed several interesting and unexpected results. In neither case did the jump across the shock cause the vortices to breakdown. However, two unusual structures were observed. The first was common to both flow fields and was seen as areas of flow reversal around the outside of the post-shock vortex. The second unexpected structure was observed only in the Mach 5.00 flow field and was seen as the formation of a trough-like structure around the outside of the post-shock vortex. Further study is needed to determine the cause of these structures. They may possibly be a result of vorticity generation due to the nonuniform pre-shock flow field combined with the shock curvature. To the best of the author's knowledge, this is the first time these two structures have been observed.

Coquart, L., Sipp, D. and Jacquin, L.

"MIXING INDUCED BY RALEIGH-TAYLOR INSTABILITY IN A VORTEX"

Physics of Fluids, Vol. 17, February 2005, 021703-1 to 021703-4

The direct numerical simulation (DNS) of a two-dimensional Lamb-Oseen vortex with a heavy internal core has been performed. Linear stability theory predicts the existence of Rayleigh-Taylor (RT)

instabilities due to the destabilizing effect of the centrifugal force on the radial flow nonhomogeneities. The DNS first exhibits wavy azimuthal perturbations which are nonlinearly distorted into bubble-like patterns, characteristic of the standard development of the RT instabilities, i.e., instabilities obtained in a planar nonhomogeneous flow in the presence of gravity. Nevertheless, important differences may be observed in the late-stage development of the instability: contrary to the standard case, the bubbles are then stretched in the azimuthal direction leading to a strong radial filamentation of the flow.

Corjon, A. and Poinso, T.

"BEHAVIOR OF WAKE VORTICES NEAR GROUND"

AIAA Journal, Vol. 35, No. 5, May 1997, pp. 849-855

Direct numerical simulations of a vortex pair embedded in a stable atmospheric boundary layer are presented. The effects of various crosswind conditions are studied. These computations demonstrate the creation of secondary vortices for the range of Reynolds numbers (3,770) to (113,100). The physics of wake vortex interactions with the ground for different values of crosswind are discussed. The redistribution of vorticity between the atmospheric boundary layer and the vorticity induced by the primary vortices may explain the vortex tilting phenomenon. A parameterization of the effect of crosswind on the minimum altitude reached by the two vortices is given.

Corjon, A. and Poinso, T.

"VORTEX MODEL TO DEFINE SAFE AIRCRAFT SEPARATION DISTANCES"

Journal of Aircraft, Vol. 33, No. 3, May-June 1996, pp. 547-553

An approximate model of wake vortices behavior is presented. We have introduced modifications in the Greene's model to consider the effects of ground (divergence, rebound) and crosswind (advection, shear). Direct numerical simulations of laminar flows with and without lateral wind are performed to validate these extensions. The first results are encouraging and efforts are carried on to derive a more reliable model. The capability of this model to mimic the reality is shown by comparison with an experimental test case.

Corjon, A. and Poinso, T.

"A MODEL TO DEFINE AIRCRAFT SEPARATIONS DUE TO WAKE VORTEX ENCOUNTER"

AIAA Paper 95-1776-CP, June 1995, San Diego, CA, pp. 117-124.

An approximate model of wake vortices behavior is presented. Based on a modification of the Greene's model, it allows to consider the effects of ground (divergence, rebound) and crosswind (advection, shear). To validate these modifications, direct numerical simulations are performed in laminar flows with and without lateral wind. The first results are encouraging and this approach will be carried on to derive a more reliable simple model.

Corjon, A. and Poinso, T.

"WAKE VORTICES BEHAVIOR NEAR THE GROUND"

ESAIM Proceedings, Vol. 1, 1996, pp. 279-294.

Direct numerical simulations of a vortex pair embedded in a stable atmospheric boundary layer are presented. The effects of various crosswind conditions are studied. These computations demonstrate the creation of secondary vortices for the range of Reynolds numbers (3,770 to 7540). The physics of wake vortex interactions with the ground for different values of crosswind are discussed. The redistribution of vorticity between the atmospheric boundary layer and the vorticity induced by the primary vortices may explain the vortex tilting phenomenon. A parameterization of the effect of crosswind on the minimum altitude reached by the two vortices is given.

Corjon, A. and Stoessel, A.

"THREE-DIMENSIONAL INSTABILITY OF WAKE VORTICES NEAR THE GROUND"

AIAA Paper No. 1997-1782, Snowmass Village, CO, June 1997

This paper presents three-dimensional direct numerical simulations of a vortex pair. The computations consider a vortex pair placed in a laminar flow field near the ground. This laminar flow is representative of a neutral surface boundary layer. The effect of variable crosswind shear on the rebound is studied with the effect of an axial wind. It is shown that long wavelength variations of the crosswind induce a curvature of the secondary vortices. This curvature is self-amplified and leads to their reconnection with the primary vortices. This linking makes them collapse. In a second part, Crow's instabilities near the ground are studied. The results show that the same phenomenon can explain the shortened lifetime of the vortices near the ground. The conclusions differ from the previous one talking about the vortex interacting with its ground image.

Corjon, A. and Valentin, J.-C.

"S.Y.A.G.E. - THE FRENCH WAKE VORTEX SPACING SYSTEM"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 33-38.

The STNA (Service Technique de la Navigation Aérienne) has been performing studies on wake vortices since 1992 for the DGAC (Direction Générale de l'Aviation Civile). Due to limited budget, the work progress is not as fast as expected. In this paper, we will present SY.A.G.E. (SYstème Anticipatif de Gestion des Espacements). This system intends to optimize the separation between aircraft at landing and take-off. All the developments done in France are related to this definition. A first version of SYAGE has been set-up and an experiment aiming at operationally verifying the system is presented. This first version concerns aircraft at departure and crosswind considerations. A wind line of seven

anemometers has been installed on Toulouse-Blagnac airport to monitor the position of the vortices. This trial should assess the needed accuracy on the wind measurement for an operational system. The constituted wind database will be used to develop short term forecasting compulsory to have the landing version of SYAGE.

Corjon, A., Bouhours, G. and Caisso, P.

"SYAGE2: 3D SONIC ANEMOMETERS WINDLINE"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

The STNA (Service Technique de la Navigation Aérienne) is performing studies on wake vortices since 1992 for the DGAC (Direction Générale de l'Aviation Civile). In this paper, we will present an experiment related to SY.A.G.E. (Système Anticipatif de Gestion des Espacements). This system intends to optimize the separation between aircraft at landing and take-off. All the developments done in France are related to this system. A first version of the experiment aiming at operationally verifying the system was running since June 1997 and its evolution is presented. This concerns aircraft at departure and crosswind considerations. A wind line of seven 3D sonic anemometers coupled with a microphone has been installed on Toulouse-Blagnac airport to monitor the lateral position of the vortices. This trial should assess the needed accuracy on the wind measurement for an operational system. The constituted wind database will be used also to develop short term forecasting compulsory to have the landing version of SYAGE. The results presented here show the efficiency of the wind line for a moderate cost.

Corjon, A., Darracq, D. and Decros, F.

"LARGE EDDY SIMULATIONS OF REBOUND AND AGING OF THREE-DIMENSIONAL WAKE VORTICES WITHIN THE ATMOSPHERIC BOUNDARY LAYER"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206233, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 145-168

Included in the presentation are details of the MFLAME Project, real test cases, including Idaho Falls experimental data, idealized test cases - concentrating on aging due to turbulence, ground effect with 3D wind, and Crow instability near the ground, theoretical modeling, lidar simulation and concluding remarks.

Corjon, A., Darracq, D. and Ducros, F.

"ATMOSPHERIC TURBULENCE EFFECTS ON WAKE VORTICES"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 65-68

The increasing traffic is constrained on the airport by the separation standards dictated by ICAO. All aircraft produce wake vortices more or less related to their gross weight. If there were no effect of the atmosphere, no decay will occur and the actual separation should have been increased. The paper will deal with the background turbulence effect on the trailing vortices. Following direct numerical simulations, CERFACS has performed large eddy simulations to reach realistic Reynolds number. The decay of the vortices induced by the turbulence is explained by vortex stretching. Due to the shear, the eddies of the atmospheric turbulence are stretched and roll around the aircraft vortices. They induce deformation that leads to Crow instability. As the turbulence level increases the vortices decay faster. Looking at the simulations, the turbulence influence on the trailing vortices is modeled by a vortex ring rolling around a rectilinear vortex. The theoretical law of decay is linear and seems to be confirmed by the simulations.

Corjon, A., Darracq, D., Champagneux, S. and Laporte, F.

"WAKE ROLL-UP SIMULATION UP TO THE FAR-FIELD"

AIAA Paper No. 1999-3201, Norfolk, VA, June-July 1999.

This paper presents a method to compute the roll-up phase and far field evolution of the vortex sheet developing behind a commercial transport aircraft using Large-Eddy Simulations (LES). The computations consider an aircraft out of ground effect and are restricted to the wake. They are initialized using either a point vortex method or experimental data, which provides the inlet plane. Then, the simulation is performed in two steps: first, steady computation of the roll-up phase using Euler simulations and second, Large-Eddy Simulations of the wake. The length of the presented far-field simulated wake is 50 wingspans and represents about 30s of flight. This method could permit to define a new standard separation matrix and also investigate new ways to accelerate vortex decay.

Corjon, A., Darracq, D., Venzac, P. and Bougeault, P.

"THREE-DIMENSIONAL LARGE EDDY SIMULATION OF WAKE VORTICES. COMPARISON WITH FIELD MEASUREMENTS"

AIAA Paper No. 1997-2309, Atlanta, GA, June 1997.

This paper presents three-dimensional large eddy simulations and two-dimensional direct numerical simulations of wake vortices of an aircraft in a realistic atmospheric boundary layer. These calculations are performed to parametrize an operational model aiming at managing the separations between aircraft at take-off and landing. The computation considered here is taken from twelve selected cases corresponding to trials made at Idaho Falls sponsored by the Federal Aviation Administration in 1990. After computing the evolution of a convective atmospheric boundary layer with a non-hydrostatic meteorological model, the evolution of the wake vortices (with their characteristics measured during the experiments) is computed. The three-dimensional behavior of the wake vortices as well as the effects of the atmospheric parameters are shown. The results of the simulations are compared to experimental data.

Corjon, A., Laporte, F. and Leweke, T.

"TOWARDS WAKE ALLEVIATION FOR TRANSPORT AIRCRAFT"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Airport congestion is a combination of several factors and the one linked to wake vortices is not obvious to solve. One of the possibilities is to act on the generating aircraft's trailing vortices. Two strategies have to be considered: (1) Suppressing completely the constraints linked to wake vortices, i.e. ensuring that the lifetime of the vortices is always shorter than the time needed to travel 2.5 nm (about 70s), whatever the meteorological conditions. Results in this direction have been obtained (uncoupled ailerons, splines), but their operational cost is too high. (2) Alleviation of the wake vortex hazard, i.e. ensuring a known level of hazard compatible with current separation standards. This approach is based on a better knowledge of the behavior of trailing vortices in the atmosphere. In fact, there is not too much difference between these two strategies. The main one is on the cost-effectiveness of such a system. A methodology has been developed that allows characterization of the wake of an Airbus type aircraft, identification of control parameters of the unique counter-rotating vortex pair that generally remains in the far wake, and control of the identified parameters. Modifying these parameters has effects on the development of short-wavelength instabilities (elliptic), long-wavelength (Crow) instability, decay in the atmosphere, and induced rolling moment. Alleviation devices based on this approach will allow to create 'older' vortices with much more favorable conditions for decay in the atmosphere and will then permit to rate the equipped aircraft in a lower class.

Corjon, A., Risso, F., Stoessel, A. and Poinso, T.

"THREE-DIMENSIONAL DIRECT NUMERICAL SIMULATIONS OF WAKE VORTICES: ATMOSPHERIC TURBULENCE EFFECTS AND REBOUND WITH CROSSWIND"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 28-1 to 28-21

This paper presents three-dimensional direct numerical simulations of a vortex pair. Two types of computations are conducted. The first type considers a vortex pair placed in a homogeneous turbulent field. The phenomenon of interaction between the vortices and the turbulence is analyzed in details from two simulations calculated on a 1353 nodes mesh grid (one case with axial core velocity, the other without). The results show that the role of large and small turbulent eddies can be separated into two independent mechanisms. The large structures are stretched by velocity gradients induced by the vortex pair. That leads to the formation of both tubes of vorticity spinning azimuthally around each vortex and associated axial velocity sheets. These turbulent structures cause a strong decrease of the maximal velocity and curvature of the vortices. These deformations of the vortex induced by the turbulence initiate an antisymmetric long-wave instability of the pair which will probably lead to the collapse of the vortices. Concurrently, the small structures can enhance the diffusion of the vorticity out of the vortex core. From this analysis and dimension considerations, the correct form for a model

of decay of the vortices is derived. The second type of computations considers a vortex pair placed in a laminar flow field near the ground. This laminar flow is representative of a neutral surface boundary layer. The effect of variable cross-wind shear is studied with the effect of an axial wind. A comparison between the two-dimensional and the three-dimensional results shows that the main phenomenon is not modified but that the altitude of rebound depends on the three components of the wind. Furthermore, the curvature of the secondary vortices due to long wavelength crosswind variation leads to their reconnection with the primary and makes them burst.

Corjon, A., Zheng, Z. C. and Greene, G. C.

"MODEL OF THE BEHAVIOR OF AIRCRAFT WAKE VORTICES EXPERIENCING CROSSWIND NEAR THE GROUND"

AIAA Paper No. 1996-2516, New Orleans, LA, June 1996

VORTEX, an approximate model of wake vortex behavior is presented. Based on a modification of the Greene's model which includes the effects of viscosity, atmospheric turbulence, and stratification, it takes into account also the effects of ground (separation, rebound) and crosswind (advection, shear). To validate these modifications, Navier-Stokes computations are performed in laminar and turbulent flows. The first comparisons are encouraging and this approach will be carried on to develop a more reliable simple model.

Cornelius, K. C.

"ANALYSIS OF VORTEX BURSTING UTILIZING THREE-DIMENSIONAL LASER MEASUREMENTS"

J. Aircraft, Vol. 32, No. 2, March-April 1995, pp. 297-306

From the analysis of experimental three-dimensional laser velocimeter data of a vortex burst condition on a generic fighter configuration, a criterion for vortex breakdown has been evaluated. The measured velocity vectors were rotated from the tunnel coordinate system to the vortex core trajectory to examine the relevant parameters for vortex instability. The Rossby parameters that govern stability were formulated in terms of the local vortex flow variables. The ratio of axial-to-crossflow energy evaluated from the data encompassing a region bounded by the vorticity provides for a parameter that is consistent with Ludwig's spiral instability analysis for conical flow. Benjamin's analysis for supercritical flow transition is correlated with a parameter for the mean flow vortex variables. The magnitudes of the critical parameters decrease downstream from the adverse pressure gradient along the vortex trajectory providing a threshold that correlates with the vortex breakdown position.

Cornish III, J. J.

"VORTEX FLOWS"

Eighth Quick-Goethert Lecture Series, The University of Tennessee Space Institute, October 1982, Tullahoma, Tennessee

The intent of the lecture is to introduce the concept of vortex flows by way of flow visualization examples, instead of attempting to rigorously define a vortex. Topics covered included vortex interactions, instabilities and breakdown, as well as wing tip vortices.

Cornman, L. B.

"AIRBORNE IN SITU MEASUREMENTS OF TURBULENCE"

In *Aviation Turbulence*, edited by R. Sharman and T. Lane, Chapter 5, 2016, Springer International Publishing Switzerland, pp. 97-120.

Airborne in situ measurements of turbulence play a key role in mitigating the operational turbulence problem for aviation. These measurements can be used for warning following aircraft, used in turbulence forecasting and nowcasting algorithms, and assisting in the development and verification of those algorithms. Furthermore, in situ measurements are useful in furthering the phenomenological understanding of turbulence in terms of climatologies and case studies. In this chapter, we focus on energy dissipation rate (EDR) calculations for both homogeneous and inhomogeneous turbulence and describe the connection between EDR and aircraft vertical acceleration response. The chapter concludes with a simulation analysis comparing EDR estimates from vertical velocity, from scaling the root mean square of the velocities and accelerations, and from scaling peak accelerations.

Cornman, L. B. and Goodrich, R. K.

"DOPPLER RADAR MEASUREMENTS OF TURBULENCE"

In *Aviation Turbulence*, edited by R. Sharman and T. Lane, Chapter 6, 2016, Springer International Publishing Switzerland, pp. 121-148.

A first-principal analysis of Doppler radar measurements of turbulence is presented. A set of limited, though practical, conditions are assumed to make the problem more tractable, with the primary condition being the discrete and finite temporal sampling of the radar signals. A theoretical derivation of the Doppler spectrum under these conditions is performed, and the distinction between what the radar actually measures and what results after a theoretical ensemble averaging is delineated. This is an important consideration, as all of the theoretical development in the literature is based upon ensemble averaging. It is shown that in the limit of an infinite number of samples, and after ensemble averaging, the Doppler spectrum can be represented by a sum of Dirac delta distributions and furthermore that the normalized spectrum will equal the probability distribution of the scatterer velocities. We show that the correlation structure of the velocity field manifests itself primarily in the square of the first moment. That is, a correlated field will have a certain degree of patchiness, which leads to variations in the first moments from realization to realization. These theoretical considerations are then studied via simulation. Parameters for a typical X-band Doppler radar are used, and correlated von Karman and uncorrelated random fields are employed. Energy dissipation rate estimates are

calculated from the simulated Doppler spectra, and the performance based on moment averaging and spectral averaging is presented. Real-world application of the turbulence measurement methods is then shown with airborne X-band detection of convective turbulence.

Cornman, L. B., Morse, C. S. and Cuning, G.

"REAL-TIME ESTIMATION OF ATMOSPHERIC TURBULENCE SEVERITY FROM IN-SITU AIRCRAFT MEASUREMENTS"

Journal of Aircraft, Vol. 32, No. 1, January-February 1995, pp. 171-177.

The quality of atmospheric turbulence detection and forecast information for the operational meteorology and aviation communities is directly linked to the quality of real-time measurements. Currently, the only direct data are subjective, qualitative, and intermittent pilot reports. This article describes techniques, suitable for real-time application on commercial transport aircraft, to generate quantitative and comprehensive turbulence measurements. These algorithms build on standard methods used in the analysis of aircraft response to turbulence, but are specifically designed to address the limitations of the available on-board data and computational resources.

Corpening, G.

"NUMERICAL SOLUTIONS TO THREE-DIMENSIONAL SHOCK WAVE / VORTEX INTERACTION AT HYPERSONIC SPEEDS"

PhD Thesis, 1988, University of Maryland, College Park, MD.

A recent study at the University of Maryland has been undertaken to numerically solve the interaction flow field between a helical-type vortex and an oblique shock wave. The study develops solutions to three-dimensional shock wave/vortex interaction at two Mach numbers, namely Mach 2.28 and 5.00. The numerical model used is based on a scheme developed by P. A. Gnoffo of the NASA Langley Research Center. It is a finite volume, implicit upwind differencing method which is used to solve the integral form of the Euler equations. In each case, a vortex was input into a flow field containing a 46.4-degree shock wave. These solutions showed several interesting results. Because of the different angles which the vortex velocity vector would strike the shock wave an asymmetry across the post-shock vortex was observed. However, neither this asymmetry nor the pressure-jump across the shock was enough to cause the vortices to breakdown. In fact, the vortex strength did not change appreciably between the input and the post-shock vortex. However, two unusual structures were observed. The first was common to both flow fields and was seen as areas of flow reversal around the outside of the post-shock vortex. The second unexpected structure was observed only in the Mach 5.00 flow field and was seen as the formation of a trough-like structure around the outside of the post-shock vortex. Further study is needed to determine the cause of these structures. They may possibly be a result of vorticity generation due to the nonuniform pre-shock flow field combined with the shock curvature. To the best of the author's knowledge, this is the first time these two structures have been observed. They presented an interesting conclusion to this study.

Corsiglia, V. R. and Dunham, Jr., R. E.

"AIRCRAFT WAKE-VORTEX MINIMIZATION BY USE OF FLAPS"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 305-338

A survey was made of research on the alleviation of the trailing vortex hazard by altering span loading with flaps on the generator airplane. Flap configurations of the generator that shed multiple vortices were found to have wakes that dispersed by vortex merging and sinusoidal instability. Reductions of approximately 50 percent in both the wake rolling moment imposed on a following aircraft and the aircraft separation requirement were achieved in the ground based and flight test experiments by deflecting the trailing edge flaps more inboard than outboard. Significantly, this configuration did not increase the drag or vibration on the generating aircraft compared to the conventional landing configuration. Ground based results of rolling moment measurement and flow visualization are shown, using a water tow facility, an air tow facility, and a wind tunnel. Flight test results are also shown, using a full-scale B-747 airplane. General agreement was found among the results of the various ground-based facilities and the flight tests.

Corsiglia, V. R. and Orloff, K. L.

"SCANNING LASER-VELOCIMETER SURVEYS AND ANALYSIS OF MULTIPLE VORTEX WAKES OF AN AIRCRAFT"

Proceedings of the Aircraft wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 114-123

A laser velocimeter capable of rapidly scanning a flow field while simultaneously sensing two components of the velocity was used to measure the vertical and streamwise velocity structure 1.5 spans downstream in the wake of a model typical of a large subsonic transport (Boeing 747). This flow field was modeled by a superposition of axisymmetric vortices with finite cores. The theoretical model was found to agree with the measured velocities everywhere except where two vortices were in close proximity. Vortex strengths derived from the span loading on the wing as predicted by vortex-lattice theory also agree with the present measurements. It was, therefore, concluded that the axisymmetric vortex model used herein is a useful tool for analytically investigating the vortex wakes of aircraft.

Corsiglia, V. R. and Rossow, V. J.

"WIND-TUNNEL INVESTIGATION OF THE EFFECT OF POROUS SPOILERS ON THE WAKE OF A SUBSONIC TRANSPORT MODEL"

NASA TM-X-73091, January 1976, NASA Ames Research Center, Moffett Field, CA

Tests were conducted in the Ames Research Center 40- by 80-Foot Wind Tunnel to determine how porosity of wing spoilers on a B-747 airplane would affect the rolling moments imposed on an aircraft

following in the wake. It was found that spoilers with 40 percent porosity and hole diameter to thickness ratio of 1.1 were just as effective in reducing the rolling moment imposed on the follower as solid spoilers, for the case of two spoilers per wing panel (6.4 percent semispan each) with a following model whose span was 20 percent of the span of the generator. When a larger following model was tested, whose span was 50 percent of that of the generator, the effectiveness of the two spoilers per wing was substantially reduced.

Corsiglia, V. R., Iversen J. D. and Orloff, K. L.

"LASER-VELOCIMETER SURVEYS OF MERGING VORTICES IN A WIND TUNNEL - COMPLETE DATA AND ANALYSIS"

NASA Technical Memorandum 78449, 1978, Ames Research Center, Moffett Field, CA

The merger of two corotating vortices was studied with a laser velocimeter designed to measure the two cross-stream components of velocity. Measurements were made at several downstream distances in the vortex wake shed by two semispan wings mounted on the wind tunnel walls. The velocity data provided well-defined contours of crossflow velocity, stream function, and vorticity for a variety of test conditions. Downstream of the merger point, the vorticity was found to be independent of the downstream distance for radii smaller than $r/b=0.05$. For larger radii, the vorticity depended on the distance from the wing. Upstream of the merger point, a multicell vorticity pattern was found.

Corsiglia, V. R., Iversen, J. D. and Orloff, K. L.

"LASER-VELOCIMETER SURVEYS OF MERGING VORTICES IN A WIND TUNNEL"

Journal of Aircraft, Vol. 15, No. 11, November 1978, pp. 762-768

The merger of two vortices was studied with a laser velocimeter designed to measure the two cross-stream components of velocity. Measurements were made at several downstream distances in the vortex wake shed by two semispan wings mounted on the wind tunnel walls. The velocity data provided well-defined contours of cross-flow velocity, stream function, and vorticity. Downstream of the merger point the vorticity was shown to be independent of the downstream distance for small radii. Upstream of the merger point a multicell vorticity pattern was shown.

Corsiglia, V. R., Jacobsen, R. A. and Chigier, N. A.

"AN EXPERIMENTAL INVESTIGATION OF TRAILING VORTICES BEHIND A WING WITH A VORTEX DISSIPATOR"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 229-242

An experimental study was carried out on a rectangular wing in the NASA-Ames 7- by 10-foot Wind Tunnel. Flow visualization studies were made using a tuft grid and smoke. Studies showed that a small vertical panel, termed a vortex dissipater, mounted on the wing upper surface near the wing tip caused

a modification of the vortex. Both the smoke and tuft grid visualization studies indicated that the dissipater caused a significant reduction in the maximum tangential velocities in the trailing vortex. Additional studies using a hot wire anemometer showed significant reductions in the magnitude of the tangential velocities, increases in the cross-sectional dimensions of the core of the dissipated vortex and changes in the turbulence structure. Limited flight tests with a dissipator fitted to a Convair-990 wing tip and using a Lear jet as a probe indicated that the rolling acceleration and the degree of roll control required was less in the modified vortex than in the unmodified vortex.

Corsiglia, V. R., Rossow, V. J. and Ciffone, D. L.

"EXPERIMENTAL STUDY OF THE EFFECT OF SPAN LOADING ON AIRCRAFT WAKES"

Journal of Aircraft, Vol. 13, No. 12, December 1976, pp. 968-973

Measurements of the rolling moment induced on a wing trailing in the wake 13.6 spans behind a subsonic transport model were made in the NASA-Ames 40-by 80-Foot Wind Tunnel. It was found that the rolling moment induced on the trailing wing was reduced substantially by reshaping the span loading on the generating model. This was accomplished by retracting the outboard trailing edge flaps. It was concluded from wind tunnel and water tow facility flow visualization studies that this flap arrangement redistributes the vorticity shed by the wing along the span to form three vortex pairs that interact to disperse the wake.

Corsiglia, V. R., Schwind, R. G. and Chigier, N. A.

"RAPID SCANNING, THREE-DIMENSIONAL HOT-WIRE ANEMOMETER SURVEYS OF WING-TIP VORTICES"

Journal of Aircraft, Vol. 10, No. 12, December 1973, pp. 752-75.

A rapid-rotation arm traversing mechanism with a three-wire, hot-wire anemometer at the tip was developed for surveying trailing vortices whose paths were distorted over long distances by wind-tunnel turbulence. Measurements were obtained behind two geometrically similar rectangular wings up to 31 span lengths in the Ames 40- by 80-foot wind tunnel. Peak tangential velocities normalized by free-stream velocity and lift coefficient decreased from 0.8 at the trailing edge to 0.6 at 31 span lengths downstream while the circulation within the core remained constant. Measured tangential velocity distributions had the same functional form as that determined by Hoffmann and Joubert.

Cosin, R., Catalano, F. M., Correa, L. G. N. and Entz, R. M. U.

"AERODYNAMIC ANALYSIS OF MULTI-WINGLETS FOR LOW SPEED AIRCRAFT"

27th International Congress of the Aeronautical Sciences, ICAS 2010, September 2010, Nice, France

An analysis of multi-winglets as a device for reducing induced drag in low-speed aircraft is carried out, based on experimental investigations of a wing-body half model at $Re = 40,000$. A baseline and six other different multi-winglets configurations were tested. The device led to 32 percent improvement in

the Oswald efficiency factor, representing an increase of 7 percent in the maximum aerodynamic efficiency. Improvements of 12 percent in the maximum rate of climb and 7 percent in the maximum range were also obtained. The pressure distribution was measured to verify global and local effects of the multi-winglets, showing only a small influence of the device on the wing loading. Structural investigations were also carried out, as well as wake surveys using a seven-hole Pitot probe that indicated significant changes in the flow field near the wingtip.

Costen, R. C.

"NONLINEAR EFFECTS OF THE DRIFT OF BUOYANT VORTICES"

AIAA Paper No. 1971-0604, Palo Alto, CA, 1971

A new equation is formulated for the motion of buoyant free vortices in an inviscid fluid. Such vortices have fluid in the core of lower density than the surrounding fluid. A criterion is given for such vortices to persist. A method is outlined for obtaining approximate solutions of the equation of motion, and results are presented for a number of cases. A horizontal buoyant vortex with positive circulation in an unbounded fluid subject to gravity drifts horizontally toward the left when viewed along its axis. Aircraft trailing vortices, if made buoyant by injection of hot gas into the vortex cores, are shown to approach each other as they descend, unless they are near the ground in which case the ground effect dominates and makes them separate. Twin buoyant vortices of like sense revolve about each other with a slower revolution rate than nonbuoyant twin vortices. Formulas are presented for calculating each of these effects.

Costen, R. C.

"DRIFT OF BUOYANT WING-TIP VORTICES"

Journal of Aircraft, Vol. 9, No. 6, June 1972, pp. 406-412

An exact solution is derived for the trochoidal motion of a single horizontal buoyant vortex drifting under gravity, and a criterion is given for such vortices to persist. Approximate solutions are obtained for the two-dimensional drift of buoyant wing tip vortices descending in a neutrally stable atmosphere where the buoyancy is achieved by injecting hot gas from the engine exhaust or auxiliary burners into the vortex cores. The vortices are found to approach each other as they descend. At low altitudes the effect may accelerate their breakup and thus reduce the period of time when wake from a large aircraft is dangerous to other aircraft. At low altitudes the ground effect may dominate and cause buoyant wing-tip vortices to separate instead of approach each other. A weakly stable atmosphere should increase the buoyancy and the convergence rate of descending wing-tip vortices, and a method is presented for calculating the combined effect of core heating and atmospheric stability.

Costen, R. C.

"AN EQUATION FOR VORTEX MOTION INCLUDING EFFECTS OF BUOYANCY AND SOURCES WITH APPLICATIONS TO TORNADOES"

NASA TN D-5964, October 1970, NASA Langley Research Center, Hampton, VA

A new equation is derived for the motion of vorticity in a general fluid, including the effects of viscosity, compressibility, nonhomogeneity, and nonconservative forces. The equation holds, in particular, for vortices which may not move with the fluid. A linearized form of the equation is applied to tornado cyclones.

Costen, R. C., Davidson, R. E. and Rogers, G. T.

"WIND-TUNNEL TESTS AND COMPUTER SIMULATIONS OF BUOYANT WING-TIP VORTICES"

Proceedings of the Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorology Society, 1974, pp. 378-386

Wind-tunnel tests have demonstrated that buoyant fluid ejected downstream at a wing tip or flap tip will enter the core of the trailing vortex and cause it to drift horizontally in accordance with the theory for buoyant-core vortices. These tests have also confirmed the results of previous experimenters that sufficiently high injection rates cause the vortices to undergo transition from small laminar cores to diffuse turbulent cores. Also, the thrust of the injection jets for this transition was shown to be less than the induced drag of the wings tested. These results indicated that placing the propulsion engines of a jet aircraft at the wing tips and flap tips would aid in alleviating the aircraft wake (1) by causing the vortices from the two wings to drift toward each other as they descend and thus break up more quickly through the Crow or burst instability, and (2) by making the vortex cores more diffuse and turbulent. Computer simulations showed that buoyant wing-tip vortices in near proximity continue to be driven together despite elongation of the cores parallel to the symmetry plane. They also showed that engine placement is critical if jet exhaust is to drive the vortices together. Random engine placement and buoyancy obtained by descent of the wake in a stable atmosphere will, in general, not promote this drift because the buoyant fluid, while wrapping around the vortices, does not always converge on their cores.

Costen, R. C., Davidson, R. E. and Rogers, G. T.

"WIND-TUNNEL TESTS AND COMPUTER SIMULATIONS OF BUOYANT WING-TIP VORTICES"

Journal of Aircraft, Vol. 13, No. 7, July 1976, pp. 495-499

Wind-tunnel tests have demonstrated that buoyant fluid ejected downstream at a wing tip or flap tip will enter the core of the trailing vortex and cause it to drift horizontally in accordance with the theory for buoyant-core vortices. This result indicates that locating the propulsion engines of a jet aircraft at the wing-tips and/or flap tips would cause the vortices from the two wings to drift toward each other as they descend, and thus break up more quickly through the Crow or burst instability. Two-

dimensional computer simulations showed that engine placement is critical because distributed buoyancy resulting from general engine placement or from descent of the wake in a stable atmosphere does not promote this drift.

Costes, M. and Kowani, G.

"AN AUTOMATIC ANTI-DIFFUSION METHOD FOR VORTICAL FLOWS BASED ON VORTICITY CONFINEMENT"

Aerospace Science and Tech., Vol. 7, No. 1, January 2003, pp. 11-21

This paper describes an automatic Vorticity Confinement procedure in order to conserve vorticity in the resolution of the compressible Euler or Navier-Stokes equations. It is based on the cancellation of the leading truncation error terms in the numerical solution of the vorticity convection equation. Application to the simple case of the convection of a 2D vortex by considering the Euler equations shows that the procedure is adequate, although some problems lie at the vortex center, probably related to the compressible character of the equations and to the singularity associated to the confinement term at the vortex center. Further analysis suggests to consider the specific vorticity instead, thus imposing a corresponding density confinement term. The first results obtained so far indicate that this way of research is promising. However, it is shown that for fine grids, a regularization treatment must also be applied at the center of the vortex because of the Vorticity Confinement singularity. Finally, a first demonstration of the applicability of the method to 3D flows is given for the case of a vortex ring.

Costes, M., Beaumier, P., Bettschart, N., Coppens, G. and Servera, G.

"COMPUTATIONAL TOOLS USED AT ONERA FOR THE DESCRIPTION OF HELICOPTER ROTOR WAKES"

AIAA Paper No. 2000-0113, Reno, NV, January 2000

This paper deals with the aerodynamic methods which are used at ONERA for the computation of helicopter rotor wakes. They are split into two classes: Lagrangian and Eulerian methods. The first class of methods includes the well-known panel methods, which are efficiently used to compute the rotor wake in forward flight, with either a prescribed geometry at high speed or a computed free wake at low speed, for descent and maneuvering conditions. These methods must generally be coupled to Eulerian CFD codes to compute the compressible unsteady flow field, which may introduce losses of accuracy significant for aero-acoustic purposes. Eulerian methods have the advantage to capture the wake, but they are penalized by their numerical diffusion which does not allow to compute the rotor wake accurately enough for aeroacoustics at the present time. However, these methods are sufficiently efficient for computing rotor performance in hover and forward flight. Furthermore, a time averaged technique using an actuator disk approach also allows to efficiently simulate the main features of rotor-fuselage interactions.

Costes, P.

"A MODEL OF THE INFLUENCE OF A VORTEX ON A FOLLOWING AIRCRAFT"

AIAA Paper No. 2000-3981, Denver, CO, August 2000.

The present paper proposes a complete analytical formulation of the interaction between an infinite vortex line, representative of the vortex system generated by a wing tip, and a following aircraft, using the lifting line aerodynamic theory, and a Lamb Oseen vortex flow field model. A quasi-exact analytical expression is obtained, which is rather complex but much more suitable to real-time simulations than the existing strip-theory model, where the wing is divided into a discrete set of wing strips, and where a compromise must be found between model precision (which needs a high number of strips) and real-time capability. The model has been validated by comparison with a wing tunnel test, and proves to be quite representative of the problem.

Cotel, A. J.

"TURBULENCE INSIDE A VORTEX: TAKE TWO"

Physics of Fluids, Vol. 14, No. 8, August 2002, pp. 2933-2934

In this paper, a modified theory based on earlier work on stratified entrainment is proposed to explain the persistence of trailing vortices in the far field. These vortices grow at a laminar rate even though the Reynolds number is high and in the turbulent regime.

Cotel, A. J. and Breidenthal, R. E.

"TURBULENCE INSIDE A VORTEX"

Physics of Fluids, Vol. 11, No. 10, October 1999, pp. 3026-3029

Following Bradshaw's analogy between rotating and stratified flows, the turbulence within a vortex is analyzed using a new model for stratified entrainment. At the vortex radius where the tangential velocity is a maximum, the model predicts that the flow is so strongly 'stratified' that even the smallest turbulent eddies are incapable of transporting fluid there. The growth of the vortex is thus limited by molecular viscosity, even though the vortex Reynolds number is large. The model prediction is compared to experiments in the literature of wingtip vortices. The result is consistent with the remarkable observations of laminar-like growth of this turbulent flow.

Coton, F. N., Galbraith, R. A. McD., Wang, T. and Newman, S. J.

"A WIND-TUNNEL BASED STUDY OF HELICOPTER TAIL ROTOR BLADE VORTEX INTERACTION"

Aeronautical Journal, May 2004, pp. 237-244

The interaction of a helicopter tail rotor blade with the tip vortex system from the main rotor is a significant source of noise and, in some flight states, can produce marked reductions in control effectiveness. This paper describes a series of wind-tunnel tests to simulate tail rotor blade vortex interaction with a view to providing data for the development and validation of numerical simulations of the phenomenon. In the experiments, which were carried out in the Argyll wind-tunnel of Glasgow University, a single-bladed rotor located in the tunnel's contraction was used to generate the tip vortex which travelled downstream into the working section where it interacted with a model tail rotor. The tail rotor was instrumented with miniature pressure transducers that measured the aerodynamic response during the interaction. The results suggest that the rotor blade vortex interaction is similar in form to that measured at much higher spatial resolution on a fixed, non-rotating blade. The combination of the two datasets, therefore, provides a valuable resource for the development and validation of predictive schemes.

Coton, F. N., Green, R. B. and Galbraith, R. A. McD.

"ANALYSIS OF MODEL ROTOR BLADE PRESSURES DURING PARALLEL INTERACTION WITH TWIN VORTICES"

Journal of Aircraft, Vol. 42, No. 6, Nov.-Dec. 2005, pp. 1553-1565

This paper presents and analyzes unsteady surface pressures measured on a model rotor blade as the blade experienced near-parallel blade-vortex interaction with a twin-vortex system. To provide a basis for analysis, the vortex system was characterized by hot-wire measurements made in the interaction plane but in the absence of the rotor. The unsteady-pressure response resulting from a single-vortex interaction is then presented to provide a frame of reference for the twin-vortex results. A series of twin-vortex interaction cases are then presented and analyzed. It is shown that the unsteady blade pressures and forces are very sensitive to the inclination angle and separation distance of the vortex pair. When the vortex cores lie almost parallel to the blade chord, the interaction is characterized by a two-stage response associated with the sequential passage of the two cores. Conversely, when the cores lie in a plane that is almost perpendicular to the blade chord, the response is like that of a single-vortex interaction. In all cases, the normal force response is consistent with the distribution of vertical velocity in the flow field of the vortex system. The pitching moment response, on the other hand, depends on the localized suction associated with the vortex cores as they traverse the blade chord.

Coton, F. N., Marshall, J. S., Galbraith, R. A. McD. and Green, R. B.

"HELICOPTER TAIL ROTOR ORTHOGONAL BLADE VORTEX INTERACTION"

Progress in Aerospace Sciences, Vol. 40, 2005, pp. 453-486

The aerodynamic operating environment of the helicopter is particularly complex and, to some extent, dominated by the vortices trailed from the main and tail rotors. These vortices not only determine the form of the induced flow field but also interact with each other and with elements of the physical structure of the flight vehicle. Such interactions can have implications in terms of

structural vibration, noise generation and flight performance. In this paper, the interaction of main rotor vortices with the helicopter tail rotor is considered, and in particular, the limiting case of the orthogonal interaction. The significance of the topic is introduced by highlighting the operational issues for helicopters arising from tail rotor interactions. The basic phenomenon is then described before experimental studies of the interaction are presented. Progress in numerical modelling is then considered and, finally, the prospects for future research in the area are discussed.

Coton, P.

"CARACTERISATION ET MODELISATION DU SILLAGE D'UN AVION A PARTIR D'ESSAIS EN VOL DE MAQUETTES EN LABORATOIRE"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 29-1 to 29-12

The paper first describes the experimental technique based on flight tests of scaled models performed in a laboratory. Some tests conducted with an Airbus A-300B2 model are presented. These tests are flow visualizations by means of smoke or helium bubbles. The first elements of a mathematical modelling of the wake behavior which has been developed for flight mechanics purposes and the further developments of this research are described. Finally, some prospecting directions concerning other non-intrusive measurement methods are presented.

Coton, P.

"A NEW FACILITY TO STUDY NEAR TO FAR VORTEX FIELDS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

With the aim of studying aircraft behavior in the low-speed domain and demonstrating the performances of new concepts the Department for System Control and Flight Dynamics of ONERA has developed over many years a specific experimental method based on flight tests of scaled models performed in a laboratory. To take off the model is propelled by means of a catapult whose height and slope angle have been previously adjusted. Once the model is launched, it flies freely without any wall or mounting interference and is recovered in a volume of plastic foam. The experimental method has the peculiarity to allow the observation and the analysis of the wakes emitted in the ground-based reference frame contrary to the experiments carried out in a wind tunnel. The access to the far field is then possible, which is a very significant asset for this type of facility compared with wind tunnels where the observations are limited to some wing spans. In the new facility B20, considering its larger dimensions in length but also in height, and taking into account the descent speed of the wake, this observation could potentially be carried out on a distance approximately 200 spans before the effect of the ground proximity influences the dynamics of the wake. As an example, this distance represents 8.5 nautical miles behind a A3XX, which largely covers the current separation distances between the planes during the approach and landing phase. The use of this laboratory, which enables gathering, under the

best operating conditions, aerodynamic data which are inaccessible in a wind tunnel, requires for this type of study the implementation of specific measurement equipment. The laser tomography is one of this equipment which makes it possible to obtain images of the flow patterns and to identify according to time the sizes and positions of the emitted vortices. Then knowing the trajectories of these vortices, precise and quantitative measurements of the velocity fields of the sown flow can be carried out by means of the PIV technique (Particle Image Velocimetry). The data thus obtained are of major importance to study and understand the mechanisms which govern the development and the evolution of the wakes. The LIDAR technique enables to use the same tools as during full-scale flight tests. A direct link can thus be established between the observations carried out in the laboratory and the results of flight tests of the plane.

Coton, P.

"STUDY OF ENVIRONMENT EFFECTS BY MEANS OF SCALE MODEL FLIGHT TESTS IN A LABORATORY"

ICAS 1998 Paper 98-3.9.1, Sept. 1998, Melbourne, Australia.

For the purpose of studying aerodynamics and aircraft behavior in the low-speed domain, ONERA has developed over many years a specific experimental method based on flight tests of scale models performed in a laboratory. This method, specially used for the characterization and modeling of the handling qualities of aircraft flying in adverse environmental conditions, is particularly well adapted to the study of non-steady phenomena. This paper first describes the facility and the main aspects of the experimental techniques. The second part is relative to the modelling concepts specially developed to represent dynamic and non-steady aerodynamic effects. These concepts are presented through some applications of the experimental technique. These applications are respectively relative to flight in atmospheric turbulence, static, dynamic and non-steady ground effects and near and far-field characterization of aircraft wake vortices.

Cottet, G.-H. and Poncet, P.

"SIMULATION AND CONTROL OF THREE-DIMENSIONAL WAKES"

Computers and Fluids, Vol. 33, 2004, pp. 697-713

We illustrate the problem of wake optimization on two examples. In the first example, the destruction of trailing vortices, we show that stochastic optimization is a flexible tool to identify vortex systems enhancing natural instabilities. In the second example, the problem of drag reduction in a cylinder wake, a priori information on the flow dynamics is highly desirable and we give some preliminary results which should be useful to select the most efficient parameters in an optimization strategy based on differential rotation of the cylinder.

Cottet, G.-H., Sbalzarini, I., Muller, S. and Koumoutsakos, P.

"OPTIMIZATION OF TRAILING VORTEX DESTRUCTION BY EVOLUTION STRATEGIES"

Proceedings of the Summer Program 2000, Center for Turbulence Research, pp. 75-82

We apply evolution strategies to optimize the instability growth of several pairs of vortices which model the wake of airplanes in landing configuration. For the case of two pairs, the evolution strategy finds a set of optimal parameters strikingly similar to those found in the linear stability analysis of Crouch (1997). The case of four pairs is also considered and leads to a larger distortion of the tip vortex.

Cottin, C., Desenfans, O., Daeninck, G. and Winckelmans, G.

"TOWING-TANK VISUALIZATIONS OF TWO-VORTEX SYSTEMS IN GROUND EFFECT"

AST4-CT-2005-012238, Catholic Univ. of Leuven, Leuven, Belgium, January 2007

The case of a longitudinally developing wake vortex pair generated by a generic wing model is investigated at a moderate, yet significant, Reynolds number through towing tank visualizations. Laser Induced Fluorescence (LIF) visualizations are performed to study qualitatively the dynamics of both the primary vortices and the separating boundary layer at the ground. The configuration is a wake vortex pair generated by a wing model following a constant altitude track, at a constant velocity above a fixed ground. Three different altitudes of wake generation In Ground Effect (IGE) are investigated: $0.5b$, $0.25b$ and $0.125b$. The reference length scale, b , is the vortex spacing as measured experimentally Out of Ground Effect (OGE).

Cottin, C., Lonfils, T., Cocle, R. and Winckelmans, G.

"ROLL-UP OF WING AND PROPELLED-WING WAKES: TIME- AND SPACE-DEVELOPING LES INCLUDING COMPARISONS TO EXPERIMENTS"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008.

A series of numerical investigations dedicated to realistic wing wakes roll-up are presented. High Reynolds number wing and propelled-wing (including cold jets) wakes were considered. Large Eddy Simulations (LES) were performed using the Vortex-In-Cell Parallel Fast Multipole (VIC-PFM) method, an efficient hybrid approach combining Lagrangian and Eulerian methods. In the present approach, the flow past the wing was not computed. Instead, the vortex sheet shed at the trailing edge was used as initial condition. Both time-developing (i.e. longitudinally periodic) and space-developing simulations were performed to evaluate the former simplified approach, widely used to reduce computational costs and to allow the simulation of such complex configurations with classical methods. The present work was organized in three successive parts. First, the effect of the velocity deficit on the roll-up and on the resulting far-field two-vortex system was investigated. A wake model was developed for the initial condition: the axial vorticity component (representative of the induced drag) is obtained by applying Prandtl lifting line theory to an elliptic wing. Second, the dynamics of a propelled wing wake was investigated using the same wake model with two additional cold jets. The characteristics were determined to represent a cruise configuration. Due to the large initial jet/vortex separation distance,

the jets have negligible effects and the dynamics are very similar to the former configuration. Finally, experimental wake data measured behind a four engine powered aircraft half-model, in high-lift configuration, were used to initialize LES of the corresponding complete wake. Instabilities like those obtained with the wake models are observed. In this case, the jet velocity penetrates the vortex core due to the short initial jet/vortex distance.

Cotton, W. and Williams, R.

"PROJECT SOCRATES: A NEW SENSOR TECHNOLOGY FOR ENHANCEMENT OF AVIATION SAFETY AND CAPACITY"

The 2002 FAA Airport Technology Conference, Atlantic City, N. J., May 5-8, 2002

Project SOCRATES is an applied research and development program aimed at exploiting sensing and processing technologies previously developed for military applications. The project objective is enhanced air safety and airport productivity, through remote, long-range detection of potentially hazardous atmospheric phenomena, using the previously untried sensing domain property of acoustics. Potential air safety applications include both ground-based and airborne systems for detecting and warning of such hazardous conditions. Airport productivity would be improved by changing the rules for separating aircraft from wake turbulence to reflect the measured location of these wakes.

Cotton, W. B.

"FOR SPACIOUS SKIES - THE 21st CENTURY PROMISE OF FREE FLIGHT"

AIAA Paper No. 2003-2667, Dayton, OH, July 2003.

The FAA's air traffic modernization programs called Free Flight Phase I and Phase II are worthwhile additions to the air traffic controller's tool kit, but they only scratch the surface of possible improvements to the flexibility and efficiency of flight under Instrument Flight Rules called for in the Free Flight definition. After systematically identifying the sources of delay and inefficiency experienced in today's air traffic management system, new operating concepts are described that overcome the bottlenecks while ensuring the continued safety of flight. Each major operating domain is examined for the delay or inefficiency-causing mechanism; airport surface, terminal area and enroute. The constraints imposed by separation minima, communications, navigation, surveillance, airspace organization and controller workload are each explored and alternative concepts proposed to remove the constraints. A system for mitigating the wake turbulence limitation is described and other airport throughput improvements are also identified. The transition from the current system to a different operating concept is the biggest challenge, and discreet steps to accomplish the transition are proposed, with incentives for aircraft operators to equip with required new onboard capabilities. The benefits to aircraft operators from all user classes, as well as to the air traffic service providers, are described, with an approximation of their value.

Cotton, W. B. and Fine, N. E.

"AIRCRAFT WAKE SAFETY MANAGEMENT SYSTEM"

U.S. Patent 2008/0030375 A1, Feb. 2008

The disclosure is directed toward a method for safely managing aircraft separation. The method comprises a data integration host configured for: receiving aircraft information from a first aircraft; receiving weather data from a weather-monitoring system; combining the aircraft information of the first aircraft with the weather data; formulating a position prediction of a wake vortex located within a critical safety volume of a runway; receiving from a sensor real time wake vortex data to the position prediction to validate the position prediction and to formulate a determination of whether the wake vortex is present in the critical safety volume; and utilizing the determination to transmit spacing data to air traffic control, wherein the spacing data is at least one of standard wake vortex spacing and minimum radar spacing.

Coulter, R. L. and Kallistratova, M. A.

"TWO DECADES OF PROGRESS IN SODAR TECHNIQUES: A REVIEW OF 11 ISARS PROCEEDINGS"

Meteorology and Atmospheric Physics, Vol. 85, 2004, pp. 3-19.

For 20 years the biennial symposia organized by the International Society for Acoustic Remote Sensing of the Atmosphere and Oceans and Associated Techniques (ISARS) have been held in different countries. The original papers collected in the proceedings of the symposia reflect the development of ideas, equipment, and methods, plus results obtained in the area. The spectrum of themes discussed at the symposia is broad. More than 60 percent of the papers were devoted to the role of SODARs in atmospheric boundary-layer research. This paper presents an overview of the development of SODAR technique as elucidated in the proceedings of 11 ISARS symposia. Topics include (1) instrumentation, (2) methods of measuring different meteorological quantities and their turbulence characteristics, and (3) validating the methods by comparison of SODAR data with in situ measurements.

Courtney, M., Wagner, R. and Lindelow, P.

"TESTING AND COMPARISON OF LIDARS FOR PROFILE AND TURBULENCE MEASUREMENTS IN WIND ENERGY"

14th International Symposium for the Advancement of Boundary Layer Remote Sensing, IOP Conf. Series: Earth and Environmental Science, Vol. 1, 2008, pp. 012021-1 to 012021-14.

Lidar profilers are beginning to gain a foothold in wind energy. Both currently available commercially systems have been extensively tested at the Hovsore facility in Denmark and valuable insights have been gained. The extensively instrumented facility will be described and some examples of the results given, illustrating the strength and weaknesses of the two contrasting profilers.

Coustols, E. and de Saint-Victor, X.

"WAKE VORTEX DYNAMICS: FROM CHARACTERISATION TO CONTROL"

Proceedings 3rd ONERA-DLR Aerospace Symposium, Paris, France, June 2001, pp. S1-2/1-14

The aim of this synthesis paper is to briefly sum-up the European research work which is under progress in the Wake Vortex field, regarding essentially dynamical aspects. Thus, these latter will involve characterization of wake vortex evolution and development of ideas for control, destruction or minimization of wake vortices intensity. Such work has been performed, for a large amount, within European projects, internal ONERA and DLR National programs. Emphasis is set upon both experimental and numerical investigations.

Coustols, E., Dor, J-B., Moens, F. and Jacquin, L.

"EXPERIMENTAL CHARACTERISATION OF THE EXTENDED NEAR-FIELD BEHIND A GENERIC-TYPE MODEL AND A VERY LARGE TRANSPORT AIRCRAFT-TYPE MODEL"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

A lot of research has been devoted to study aircraft wake vortices in order to understand their formation and development, to predict their decay and, then, to try to minimize their intensity, to disorganize their far-wake field evolution by suggesting approaches with potential to safely reduce such separation distances. Two experimental investigations have been recently defined and conducted in a low-speed research-type wind tunnel (F2 testing facility from ONERA Centre of Fuga-Mauzac). The steady and unsteady properties of the wake have been scrutinized to few wing spans downstream of the models, using 3D Laser Doppler Velocimetry and hot-wire anemometry. Mean and turbulent quantities, vorticity distributions in the wake as well as vortex trajectories will be provided and discussed in detail for the base line configuration.

Coustols, E., Geffroy, P. and Jacquin, L.

"EXPERIMENTAL CHARACTERISATION OF WAKES IN THE EXTENDED NEAR-FIELD BEHIND GENERIC-TYPE AND TRANSPORT AIRCRAFT-TYPE MODELS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

To avoid any vortex hazardous encounter, minimum separation distances are imposed to aircraft on airport approach, under instrument flight rules. The separation rules, established in the early 1970's, should be re-examined according to the present and on-going knowledge about wake vortex formation and development. Such distances are a major source for airport congestion and delay, which could be relieved by reducing wake vortex impact on the following aircraft without degrading today's high safety standards. It is therefore mandatory to study aircraft wake vortex in order to understand their formation, development, and far-field behavior, to predict their decay and, then, to try to minimize their intensity, to disorganize or even destroy the vortices by suggesting approaches with potential to

safely reduce the separation distances. Depending upon model scale, the steady properties of the wake have been scrutinized to about five to nine wing spans downstream of the model, using complementary measurement techniques: laser sheet visualizations, hot-film, 5-hole probing and 3D Laser Doppler Velocimetry. The presentation summarizes wake vortex formation and evolution obtained for two specific sets of experiments. Mean and turbulent quantities, vorticity distributions in the wake as well as vortex trajectories will be provided and discussed in detail for the base line configurations. Furthermore, the outcome of the first attempts to control the wake vortices, using either flap and wing tip devices for the A300 model or spoiler type add-on devices for the SWIM model, will be also briefly evoked. It is therefore desirable that the consistent data base, generated from these two experiments, could be devoted to validate CFD tools for wake vortex prediction, within the framework of European projects or outside of them.

Coustols, E., Jacquin, L. and Schrauf, G.

"STATUS OF WAKE VORTEX ALLEVIATION IN THE FRAMEWORK OF EUROPEAN COLLABORATION: VALIDATION ATTEMPTS USING TESTS AND CFD RESULTS"

European Conference on Computational Fluid Dynamics (ECCOMAS CFD 2006), 2006, Technical University of Delft, Delft, The Netherlands.

This document provides a synthesis of recent research studies that have been conducted in the last decade within several European projects from the 5th and 6th Framework Programs. All these studies aimed at a better characterization of aircraft wake vortices and then at their subsequent control. In the latter case, the goal is to minimize the strength of such vortices in the far-field. At first, characterization of wake vortex using complementary tools (testing facilities, flight tests, simulations and theory) will be briefly evoked. Secondly, information will be provided on the main principles for wake vortex alleviation. At last, results and then recommendations will be detailed from the considered practical approaches.

Coustols, E., Jacquin, L., Moens, F. and Molton, P.

"STATUS OF ONERA RESEARCH ON WAKE VORTEX IN THE FRAMEWORK OF NATIONAL ACTIVITIES AND EUROPEAN COLLABORATION"

European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS 2004, Jyväskylä, Finland, July 2004

This document provides a synthesis of recent experimental research studies conducted at ONERA, aiming at a better characterization of aircraft wake vortex and its control. Thus, either generic, two-engine or four-engine transport aircraft-type models have been considered in existing complementary facilities from ONERA, being the most appropriate for scrutinizing different stages of wake evolution. Main results from several research programs are discussed. They have been obtained both from National and European activities, although emphasis has been set on the 5th Framework Program project 'C-Wake: Wake Vortex Characterization and Control'.

Coustols, E., Labbe, O., Moens, F., Molton, P. and Jacquin, L.

"STATUS OF ONERA RESEARCH ON WAKE VORTEX EVOLUTION AND ALLEVIATION IN THE FRAMEWORK OF NATIONAL ACTIVITIES AND EUROPEAN COLLABORATIONS"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

Projects and research programs dealt with both experimental and numerical investigations to characterize the wake flow field generated by generic very large or standard four-engine large transport-type aircraft models. Highly documented data bases were generated from various facilities up to full-scale flight trials. The different stages of the wake evolution were identified from two complementary ONERA facilities, using the most appropriate measurement techniques: the ONERA DSFM F2 low speed wind tunnel for scrutinizing the wake flow field down to couple of wing spans behind the model (near to extended near-wake field), the ONERA Lille free-flight B10 and B20 catapult facilities for focusing on the wake field more far downstream i.e., between 20 and 100 wing spans behind the model (mid- to far-wake fields). Additionally, means for control or minimizing wake vortex intensity through either devices or concepts have been deeply investigated. From extensive studies in the near- and extended near-wake field at the ONERA F2 wind tunnel, high-lift wing configurations were selected from specific flap arrangement, appropriate for wing loading variations, using a generic four-engine type aircraft model. Such tests confirmed the generation of a rather powerful vortex in the inner part of the wing, either co-rotating or counter-rotating with the ones generated at the outer part of the wing. Tests conducted at the free-flight catapult facilities allowed to show up the real potential of such a wing loading modification for altering vortex trajectories, by creating either closer or wider resulting vortices in the mid-wake field, inducing either larger or weaker descent speed. In parallel to testing campaigns, numerical simulations of the wake-vortex development behind an aircraft in high-lift configuration were performed from the near- to the mid-wake field.

Coustols, E., Prudhomme, S., Mignosi, A. and Destarac, D.

"REAR FUSELAGE FLOW STUDIES ON A MODERN TRANSONIC TRANSPORT AIRCRAFT"

J. Aircraft, Vol. 32, No. 6, November-December 1995, pp. 1183-1190

An experimental program was set up in the CERT/ONERA's T2 wind tunnel, which is transonic, pressurized, and has self-adaptive walls. A 1/80th-scale model of a modern transonic transport aircraft was tested in two configurations: 1) fuselage without horizontal stabilizer and 2) fuselage with horizontal stabilizer. Various measurements were performed: oil-flow visualizations, pressure distributions, boundary-layer surveys along the fuselage symmetry lines using a three-dimensional laser Doppler anemometry system, and wake surveys with both pressure and velocity measurements in a plane downstream of the fuselage base. Moreover, both inviscid and viscous computations were carried out separately under experimental conditions. This article reports a detailed analysis of the computations and experiments conducted on the model in both configurations; the objective of this study was to reach a better understanding of the flows developing along the rear part of a fuselage.

Coustols, E., Seraudie, A. and Mignosi, A.

"REAR FUSELAGE TRANSONIC FLOW CHARACTERISTICS FOR A COMPLETE WING-BODY CONFIGURATION"

J. Aircraft, Vol. 34, No. 3, May-June 1997, pp. 337-345

The study presents results for experiments conducted in the transonic pressurized T2 wind tunnel of Centre d'Etudes et de Recherches de Toulouse. The 1/80th scale model of a modern subsonic transport aircraft was mounted in the test section using a fin-sting. It consisted of a fuselage, a detachable horizontal rear stabilizer, a belly fairing, and tip-truncated wings. The tip-truncated wings were designed by Aerospatiale to reproduce the correct downwash in the rear fuselage region. Tests were conducted at a freestream Mach number of 0.82 and a Reynolds number evaluated with the model chord length of approximately $2.5 \times 1,000,000$. Various measurements were performed, mainly in the vicinity of the fuselage downstream rear part: oil-flow visualizations, pressure distributions, boundary-layer surveys along the fuselage symmetry lines and some lateral lines using a laser Doppler anemometry system, and near-wake surveys with both pressure and velocity measurements. These experiments were designed to allow a fine description of the flows developing along the rear part of a fuselage in a configuration similar to actual flight applications.

Coustols, E., Stumpf, E., Jacquin, L., Moens, F., Vollmers, H. and Gerz, T.

"MINIMISED WAKE': A COLLABORATIVE RESEARCH PROGRAMME ON AIRCRAFT WAKE VORTICES"

AIAA Paper No. 2003-0938, Reno, NV, January 2003.

The aim of this paper is to present the Collaborative Research Program on aircraft wake vortices between ONERA and DLR which was launched in 1999. Results of experimental investigations carried out within this framework are provided, with special emphasis set upon very large transport aircraft-type applications.

Cox, C. I., Fairbanks, M. C. and McCulloch, R. A.

"FUNCTIONAL DESIGN SPECIFICATION OF A MODEL OF AIRCRAFT WAKE VORTICES"

TR-92/232, Oct. 1992, Smith System Engineering, UK

This report is the functional design specification for a model of the formation, motion, and decay of aircraft wake vortices. The model will simulate the formation of the vortices behind the wing using a standard implementation of the point vortex method. The effects of engines will be included using additional point vortices with random circulations. After merging into a vortex pair, the properties of the vortices will be extracted to give expressions for the strength, separation, and turbulence level of the vortices. The model will simulate the evolution of the vortex pair by integrating the coupled equations which describe their motion and decay. The method is based on a standard description of

vortex behavior at high altitudes, adapted to take account of the interactions between vortices and the ground.

Cox, G., Billheimer, B., Reisweber, M., Greenhaw, R., Savage, J. and Walls, J.

"REDUCTION OF DIAGONAL SEPARATION FROM 1.5 NAUTICAL MILES TO 1.0 NAUTICAL MILE FOR PARALLEL DEPENDENT APPROACHES"

DOT-FAA-AFS-400-83, February 2014, FAA Flight Technologies and Procedures Division, Oklahoma City, OK.

The Federal Aviation Administration Flight Standards (AFS) Closely Spaced Parallel Operations team evaluated the risk of dual dependent parallel operations associated with reducing the diagonal separation between aircraft from 1.5 Nautical Miles (NM) to 1.0 NM for parallel dependent approaches at runway centerline spacing (RCLS) of 2,500 feet or greater and less than or equal to 4,300 feet. The FAA Safety Management System acceptable level of risk of 0.000000001 per operation was used as the success criteria. The results show that the risk is acceptable up to an RCLS of 3,600 feet when utilizing the final controller to mitigate final approach course deviations and to accommodate reduction of in-trail spacing at the Final Approach Fix.

Craft, T. J., Gerasimov, A. V., Launder, B. E. and Robinson, C. M. E.

"A COMPUTATIONAL STUDY OF THE NEAR-FIELD GENERATION AND DECAY OF WINGTIP VORTICES"

International Journal of Heat and Fluid Flow, Vol. 27, Issue 4, August 2006, pp. 684-695

The numerical prediction of the downstream trailing vortex shed from an aircraft wingtip is a particularly challenging CFD task because, besides predicting the development of the strong vortex itself, one needs to compute accurately the flow over the wing to resolve the boundary layer roll-up and shedding which provide the initial conditions for the free vortex. Computations are here reported of the flow over a NACA 0012 half-wing with rounded wing tip and the near-field wake as measured by Chow, J. S., Zilliac, G., Bradshaw, P., 1997. The aim is to assess the performance of two turbulence models which, in principle, might be seen as capable of resolving both the three-dimensional boundary layer on the wing and the generation and near-field decay of the strongly accelerated vortex that develops from the wingtip. Results using linear and non-linear eddy-viscosity models are presented, but these both exhibit a far too rapid decay of the vortex core. Only a stress-transport (or second-moment) model that satisfies the 'two-component limit' reproduces the principal features found in the experimental measurements.

Craft, T., Iacovides, H., Launder, B. and Zacharos, A.

"SOME SWIRLING-FLOW CHALLENGES FOR TURBULENT CFD"

Flow Turbulence Combustion, Vol. 80, 2008, pp. 419-434.

This paper examines some of the continuing challenges, within a RANS framework, of computing turbulent swirling flows such as are encountered in industry and the environment. The principal focus is on modeling turbulent transport processes but serious problems also arise in handling numerical issues, too. Recent researches of two of these types of flow by the authors and their colleagues are examined; namely, the confined flow within a rotor-stator disc cavity and the trailing wing-tip vortex. The former flow, while geometrically axisymmetric, has been found to create multiple rotating vortices necessitating a three-dimensional time-dependent analysis. The wing-tip vortex is extremely sensitive to the choice of turbulence model and only a second-moment closure that complies with constraints of two-component turbulence has been found capable of handling both the flow over the wing and the wake vortex. Moreover, because of the large distances downstream of the aircraft to which, for practical cases, computations need to be carried, the numerical strategy is brought into question. Finally, arising from these two test cases, outline remarks are made about a swirling flow that poses one of the major computational challenges of the twenty-first century.

Cramer, M. and Rodriguez, L.

"ANALYSIS OF AIRCRAFT LATERAL PATH TRACKING ACCURACY AND ITS IMPLICATIONS FOR SEPARATION STANDARDS"

2013 Integrated Communications Navigation and Surveillance (ICNS) Conference, April 2013, Herndon, VA.

Application of Area Navigation (RNAV) and Required Navigation Performance (RNP) to aircraft separation continues to be a point of difficulty which frequently centers on defining statistical models for Performance-Based Navigation (PBN). Given that questions of the statistics associated with position estimation error are fairly well known, and that path definition error is near zero in modern RNP avionics, this paper will focus on path steering error, which has not been studied using operational data. We propose analysis methods that can be applied to analyzing large volumes of recorded, in-service data to answer the questions of statistical modeling for the path following behavior of these systems. Preliminary analysis results derived from partner airlines' RNAV and RNP equipped aircraft flying in revenue service are presented.

Craven, A. H. and Alexander, A. J.

"AN INVESTIGATION OF VORTEX BREAKDOWN AT MACH 2"

CoA Note Aero 158, November 1963, Cranfield University, Cranfield, Bedfordshire, UK.

Wind tunnel tests have been made at $M = 2$ on a 75 deg swept delta wing to study the progressive breakdown of the leading-edge vortices, which occurs at high incidence. The incidence at which vortex breakdown occurred at supersonic speeds was somewhat less than at low speeds, but the pattern of breakdown appeared to be similar, although the spiraling region of flow is much larger at supersonic speeds. Quite slender objects placed downstream of the wing had appreciable upstream effects,

causing vortex breakdown to move upstream by as much as 20% of the root chord for the same incidence.

Credeur, L.

"BASIC ANALYSIS OF TERMINAL OPERATION BENEFITS RESULTING FROM REDUCED VORTEX SEPARATION MINIMA"

NASA TM 78624, October 1977, NASA Langley Research Center, Hampton, VA

The impact of reducing the wake vortex minimum separation required behind heavy jets on terminal area operation rate was analyzed. The effect on arrival saturation and steady state average delay was determined for various percentages mix of heavy and large jet traffic samples operating under various precision of interarrival spacing. Benefits increase with percentage of heavy aircraft and with precision of control. These results demonstrate the payoff possible from research to reduce the severity of the trailing vortex by aerodynamic means.

Credeur, L. and Perry, R. B., editors

"PROCEEDINGS OF THE NASA FIRST WAKE VORTEX DYNAMIC SPACING WORKSHOP"

NASA/CP-97-206235, November 1997, NASA Langley Research Center, Hampton, VA

A Government and Industry workshop on wake vortex dynamic spacing systems was conducted on May 13-15, 1997, at the NASA Langley Research Center. The purpose of the workshop was to disclose the status of ongoing NASA wake vortex R&D to the international community and to seek feedback on the direction of future work to assure an optimized research approach. Workshop sessions examined wake vortex characterization and physics, wake sensor technologies, aircraft/wake encounters, terminal area weather characterization and prediction, and wake vortex systems integration and implementation. A final workshop session surveyed the Government and Industry perspectives on the NASA research underway and related international wake vortex activities. This document contains the proceedings of the workshop including the presenters' slides, the discussion following each presentation, the wrap-up panel discussion, and the attendees' evaluation feedback.

Cremer, M. and Ronig, S.

"IN-FLIGHT MEASUREMENT SYSTEM FOR WAKE VORTEX VELOCITY FIELDS"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

The Research Aircraft DO 128-6 of the TU Braunschweig is capable of measuring pilot inputs, flight path and aircraft reactions while encountering wake vortices. The aircraft is equipped with flow direction probes on a nose boom, at the wing tips and the vertical fin for measurements of a wake vortex field. DGPS is used to determine the exact position behind the vortex generating aircraft. With

the measured vortex position and strength, it is possible to validate numeric models for wake vortices and wake vortex encounters.

Crescenti, G. H.

"THE DEGRADATION OF DOPPLER SODAR PERFORMANCE DUE TO NOISE: A REVIEW"

Atmospheric Environment, Vol. 32, No. 9, 1998, pp. 1499-1509

Ambient background noise is a common problem for poor Doppler sodar performance. This noise can be active or passive and broad-band or narrow-band. Active broad-band noise decreases the sounding range of the sodar by decreasing the signal-to-noise ratio. Active narrow-band noise can be interpreted as erroneous wind values. Passive noise sources are objects which reflect the transmitted acoustic pulse back to the sodar with zero Doppler shift. Use of acoustic shielding is discussed as a method of noise pollution control by isolating the side lobe energy of the transmitted acoustic pulse. At the same time, these acoustic shields are effective in blocking out active ambient background noise. Previous studies which experienced noise interference are shown as examples of problems that are frequently encountered.

Crick, P.

"EVALUATION OF TWO HAZARD IDENTIFICATION TECHNIQUES IN THE CONTEXT OF TIME BASED AIRCRAFT SEPARATIONS"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

Up to now, no research project at the Eurocontrol Experimental Centre (EEC) impacting Air Traffic Management (ATM) has been accompanied by a formal safety assessment. This is to change as in future all such projects must be ESARR4 compliant. The need arises therefore to find one or more suitable methodologies that can be used to demonstrate that a project is ESARR4 compliant. In essence, this requires that risks be identified and assessed and corresponding mitigating actions be defined. The EATM Safety Assessment Methodology (SAM) is one possible means to demonstrate that a project complies with ESARR4. It aims at recommending one or more suitable techniques depending on the nature and status of the project in question. A survey of over 600 safety methodologies has recently been carried out and several suitable candidate methodologies have been identified. Two of these methodologies were selected for an in-depth evaluation focusing on human factors (people and procedures) elements: HAZOP (HAZard and Operability study) and TRACEr (Technique for the Retrospective and Predictive Analysis of Cognitive Errors in ATM). These were applied to three current projects at the EEC. One of these projects was the Time-Based Separations project. Both methodologies were found to have their applications: HAZOP could be recommended to be used at an early stage of a project to refine the concept whereas TRACEr could be used to analyze core tasks and to identify critical, high level errors as well as to contribute towards refining operational procedures.

Crider, D. A.

"THE NEED FOR UPSET RECOVERY TRAINING"

AIAA Paper 2008-6864, August 2008, Honolulu, Hawaii.

Several aviation accidents have occurred over the years, many in this decade, which have involved upsets from normal flight. Sometimes these upsets occurred slowly without the pilot noticing the departure until reaching an unusual attitude. Others occurred abruptly, such as those caused by a stall, whether early due to icing or other environmental factors, or at the normal point due to human action or inaction. Other abrupt departures have been caused by mechanical factors or environmental factors, such as aircraft wakes. Given the potentially serious consequences of such upsets, the ability to recover is an important part of pilot training. Accordingly, a comprehensive, well-conceived training program will necessarily address the various types of upset scenarios that may lead to accidents, the need to avoid negative transfer of training and, for accidents involving stalls, the need to accommodate simulator model aerodynamic data envelope limitations. Many, if not most, upsets remain within the aerodynamic data envelope such that current aerodynamic model limits would not be exceeded when these scenarios are simulated. Motion cueing is another issue for many upset training scenarios. This paper will present short case studies of several upset aircraft accidents and incidents, classified to gain insight into the training requirement for each scenario. The history of related National Transportation Safety Board recommendations and actions to date will also be discussed.

Criminale, W. O., Lasseigne, D. G. and Jackson, T. L.

"VORTEX PERTURBATION DYNAMICS"

ICASE Report No. 95-52, Hampton, VA, July 1995

An initial value approach is used to examine the dynamics of perturbations introduced into a vortex under strain. Both the basic vortex considered and the perturbations are taken as fully three-dimensional. An explicit solution for the time evolution of the vorticity perturbations is given for arbitrary initial vorticity. Analytical solutions for the resulting velocity components are found when the initial vorticity is assumed to be localized. For more general initial vorticity distributions, the velocity components are determined numerically. It is found that the variation in the radial direction of the initial vorticity disturbance is the most important factor influencing the qualitative behavior of the solutions. Transient growth in the magnitude of the velocity components is found to be directly attributable to the compactness of the initial vorticity.

Crisp, V. K.

"WAKE VORTEX SYSTEMS COST/BENEFITS ANALYSIS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 509-519

The goals of cost/benefit assessments are to provide quantitative and qualitative data to aid in the decision-making process. Benefits derived from increased throughput (or decreased delays) are used to balance life-cycle costs. Packaging technologies together may provide greater gains (demonstrate higher return on investment).

Critchley, J. B.

"WAKE VORTEX: THE PROGRAMME IN THE UNITED KINGDOM"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 6-1 - 6-13

The UK program of work can be divided into three broad subject areas. The first area is the monitoring of the existing criteria. This has been done through the UK wake vortex incident reporting scheme and the associated database. The second area covers techniques or devices which would make use of the existing basic theoretical and practical understanding of wake vortex behavior and parameters. Lasers and radar are being investigated to see if the controller can be provided with information on vortices to help decide whether criteria can or cannot be relaxed. The third area considers longer term objectives such as increasing the number of categories of aircraft and providing computer assistance to controllers.

Critchley, J. B. and Foot, P. B.

"UNITED KINGDOM CIVIL AVIATION AUTHORITY WAKE VORTEX DATABASE: ANALYSIS OF INCIDENTS REPORTED BETWEEN 1982 AND 1990"

CAA Paper 91015, August 1991, Civil Aviation Authority, London, UK.

The report analyses wake vortex incidents reported to the Civil Aviation Authority between 1982 and 1990, focusing on Heathrow approaches. The analysis covers incident rates related to month of the year, traffic levels, aircraft separations, periods of the day and wind conditions; the occurrence rates for various leader and follower aircraft types are given, and the need for a review of separation standards is identified.

Critchley, J. B. and Foot, P. B.

"UNITED KINGDOM CIVIL AVIATION AUTHORITY WAKE VORTEX DATABASE: ANALYSIS OF INCIDENTS REPORTED BETWEEN 1982 AND 1990"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 8-1 - 8-18

The objective of this paper is to report the results of an analysis of the UK Wake Vortex Incident Database. The United Kingdom Civil Aviation Authority (CAA) has been operating a scheme since 1972 for the reporting, monitoring, and analysis of wake vortex incidents. The data for each incident come

from several sources: initially from the pilots of the leader and follower aircraft involved in an incident, the UK Meteorological Office, digitally recorded radar data from Air Traffic Control Centers and, in some cases, from the flight data recorders of the aircraft involved. The wake vortex database was computerized in 1983 and the details of each incident were recorded on the database, which is currently maintained by the CAA's ATC Evaluation Unit. Since 1982, the UK has used 4 wake vortex weight categories instead of the 3 categories used by ICAO. Because the wake vortex separation criteria for use in the UK were last changed in 1982, the analysis has been confined to the period 1982 to 1990. In this period there were 515 incidents, 392 of which occurred on the approach to Heathrow.

Crnojevic, C., Florent, P. and Decool, F.

"SWIRL MEASUREMENTS IN A MOTOR CYLINDER"

Experiments in Fluids, Vol. 26, 1999, pp. 542-548.

The present article analyzes different definitions of the swirl number and their application to control the mixing process in the cylinder of direct injection diesel engines. We first discuss the origins of the existing methods used to control swirl, which are usually based on the presence of a stirring device, or rotometer, in the cylinder head. A new possibility is then proposed for determining the swirl number, based on equivalent angular velocity, and a comparison made of results obtained using the different techniques available for measuring swirl in motor cylinders.

Crockett, D.

"HOW TO DEAL WITH INDUCED TURBULENCE"

Flight Safety Foundation, Helicopter Safety, Vol. 14, No. 5, September/October 1988, pp. 1-4.

Knowing the conditions of vortex generation and its characteristics will assist a pilot in better negotiating this phenomenon in flight.

Croom, D. R.

"EVALUATION OF FLIGHT SPOILERS FOR VORTEX ALLEVIATION"

Journal of Aircraft, Vol. 14, No. 8, August 1977, pp. 823-825

The strong vortex wakes generated by large transport aircraft are a potential hazard to smaller aircraft, and so NASA is involved in a program of model tests, flight tests, and theoretical studies to determine the feasibility of reducing this hazard by aerodynamic means. This note summarizes the wind tunnel and full-scale flight investigations of the flight spoilers that exist on the wide-bodied transport jet aircraft when used as trailing vortex hazard alleviation devices. Existing flight spoilers on the B-747 airplane were found to be effective as trailing vortex attenuators.

Croom, D. R.

"LOW-SPEED WIND-TUNNEL PARAMETRIC INVESTIGATION OF FLIGHT SPOILERS AS TRAILING-VORTEX-ALLEVIATION DEVICES ON A TRANSPORT AIRCRAFT MODEL"

NASA TP-1419, April 1979, NASA Langley Research Center, Hampton, VA

An investigation was made in the Langley V/STOL tunnel to determine, by the trailing-wing sensor technique, the effectiveness of 11 combinations of the existing flight-spoiler segments on a jumbo-jet transport aircraft model when they were deflected as trailing-vortex-alleviation devices. All 11 of the flight-spoiler configurations investigated were effective in reducing the induced rolling moment on the trailing model by as much as 18 to 67 percent at a distance of 7.8 transport wing spans behind the transport aircraft model. The present investigation is an extension of earlier wind-tunnel and flight tests which showed that the existing flight spoilers on the jumbo-jet aircraft can be used as effective trailing-vortex-alleviation devices. Essentially all the reduction in induced rolling moment on the trailing-wing model was realized at a spoiler deflection of 45 deg. for single-spoiler configurations, 30 deg. for two-spoiler configurations, and 15 deg. for both the three- and four-spoiler configurations. Of the 11 flight-spoiler configurations investigated, the most promising configuration for trailing-vortex abatement on the jumbo-jet aircraft appears to be the three inboard flight spoilers deflected 15 deg. This configuration reduced induced rolling moment on the trailing-wing model by 65 percent and increased drag coefficient on the transport aircraft model by about 0.012 at a trim lift coefficient of 1.2.

Croom, D. R.

"LOW-SPEED WIND-TUNNEL INVESTIGATION OF FORWARD-LOCATED SPOILERS AND TRAILING SPLINES AS TRAILING-VORTEX HAZARD-ALLEVIATION DEVICES ON AN ASPECT-RATIO-8 WING MODEL"

NASA TM X-3166, February 1975, NASA Langley Research Center, Langley Station, VA

An investigation was made in the Langley V/STOL tunnel to determine, by the trailing-wing sensor technique, the effectiveness of either a forward-mounted spoiler or a tip-mounted spline as trailing-vortex attenuation devices on an upswept aspect-ratio-8 wing model. The trailing-wing rolling-moment data taken in the tunnel diffuser section show good agreement with the data taken in the tunnel test section. This agreement indicates that reasonable results may be obtained in the Langley V/STOL tunnel in experimental investigations of the trailing-vortex hazard at relatively great distances behind aircraft models.

Croom, D. R.

"THE DEVELOPMENT AND USE OF SPOILERS AS VORTEX ATTENUATORS"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 339-368

This paper presents the results of ground-based and flight investigations performed at NASA to develop spoilers as trailing vortex alleviation devices. Based on the results obtained in these investigations, it was found that the induced rolling moment on a trailing model can be reduced by

spoilers located near the mid-semispan of a vortex-generating wing. Substantial reductions in induced rolling moment occur when the spoiler vortex attenuator is located well forward on both unswept and swept wing models. In addition, it was found that existing flight spoilers on the jumbo-jet transport aircraft can be effective as trailing vortex attenuators.

Croom, D. R.

"DEVELOPMENT OF SPOILERS AS TRAILING-VORTEX HAZARD ALLEVIATION DEVICES"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 217-228

This paper presents the results of ground-based and flight investigations that have been performed at NASA for the purpose of development of spoilers as trailing-vortex hazard alleviation devices. Based on the results obtained in these investigations, it was found that the induced rolling moment on a trailing model can be reduced by spoilers located near the mid-semispan of a vortex-generating wing. Substantial reductions in induced rolling moment occur when the spoiler vortex attenuator is located well forward on both unswept and swept wing models. In addition, it was found by ground-based model tests and verified by full-scale flight tests that the existing flight spoilers on the B-747 aircraft are effective as trailing vortex attenuators. Based on the results of wind-tunnel investigations of the DC-10-30 and L-1011 airplane models, the existing flight spoilers on both the DC-10-30 and L-1011 airplanes may also be effective trailing vortex attenuators.

Croom, D. R. and Dunham, Jr., R. E.

"LOW-SPEED WIND-TUNNEL INVESTIGATION OF SPAN LOAD ALTERNATION, FORWARD-LOCATED SPOILERS, AND SPLINES AS TRAILING-VORTEX-HAZARD ALLEVIATION DEVICES ON A TRANSPORT AIRCRAFT MODEL"

NASA TN D-8133, December 1975, NASA Langley Research Center, Hampton, V.

An investigation was made in the Langley V/STOL tunnel to determine the effectiveness of a forward-located spoiler, a spline, and a span load alteration due to a flap configuration change as trailing-vortex-hazard alleviation methods. For the transport aircraft model in the normal approach configuration, the results indicate that either a forward-located spoiler or a spline is effective in reducing the trailing-vortex hazard. The results also indicate that large changes in span loading, due to retraction of the outboard flap, may be an effective method of reducing the trailing-vortex hazard.

Croom, D. R. and Holbrook, G. T.

"LOW-SPEED WIND-TUNNEL INVESTIGATION OF WING FINS AS TRAILING-VORTEX-ALLEVIATION DEVICES ON A TRANSPORT AIRPLANE MODEL"

NASA TP-1453, June 1979, NASA Langley Research Center, Hampton, VA

An investigation was made in the Langley V/STOL tunnel to determine, by the trailing-wing sensor technique, the trailing-vortex-alleviation effectiveness of both a one- and a two-fin configuration (semicircular with a radius of 0.043 semispan) on a jumbo-jet transport airplane model in its landing configuration. The fins were located on the upper surface of the transport model wing along the 30-percent-chord line. The fin configurations were effective in reducing the vortex-induced rolling moment, by amounts varying from 28 to 60 percent, on the trailing wing model located at a distance of 7.8 transport model wing spans downstream of the transport model. The flow over the fins and over the transport airplane model wing downstream of the fins was observed to be separated and turbulent. All fin configurations caused a reduction in maximum lift coefficient, a positive increment in drag coefficient, and an increment in nose-up pitching-moment coefficient on the transport airplane model.

Croom, D. R., Vogler, R. D. and Thelander, J. A.

"LOW-SPEED WIND-TUNNEL INVESTIGATION OF FLIGHT SPOILERS AS TRAILING-VORTEX-ALLEVIATION DEVICES ON AN EXTENDED-RANGE WIDE-BODY TRI-JET AIRPLANE MODEL"

NASA TN D-8373, December 1976, NASA Langley Research Center, Hampton, VA

An investigation was made in the Langley V/STOL tunnel to determine, by the trailing-wing sensor technique, the effectiveness of various segments of the existing flight spoilers on an extended-range wide-body tri-jet transport airplane model when they were deflected as trailing-vortex-alleviation devices. On the transport model with the approach flap configuration, the four combinations of flight-spoiler segments investigated were effective in reducing the induced rolling moment on the trailing wing model by as much as 25 to 45 percent at downstream distances behind the transport model of 9.2 and 18.4 transport wing spans. On the transport airplane model with the landing flap configuration, the four combinations of flight-spoiler segments investigated were effective in reducing the induced rolling moment on the trailing wing model by as much as 35 to 60 percent at distances behind the transport model of from 3.7 to 18.4 transport wing spans, 18.4 spans being the downstream limit of distances used in this investigation.

Croom, D. R., Vogler, R. D. and Williams, G. M.

"LOW-SPEED WIND-TUNNEL INVESTIGATION OF FLIGHT SPOILERS AS TRAILING-VORTEX-ALLEVIATION DEVICES ON A MEDIUM-RANGE WIDE-BODY TRI-JET AIRPLANE MODEL"

NASA TN D-8360, November 1976, NASA Langley Research Center, Hampton, VA

An investigation was made in the Langley V/STOL tunnel to determine, by the trailing-wing sensor technique, the effectiveness of various segments of the existing flight spoilers on a medium-range wide-body tri-jet transport airplane model when they were deflected as trailing-vortex-alleviation devices. The four combinations of flight-spoiler segments investigated were effective in reducing the induced rolling moment on the trailing wing model by as much as 15 to 60 percent at distances behind the transport model of from 3.9 to 19.6 transport wing spans, 19.6 spans being the downstream limit

of distances used in this investigation. Essentially all of the reduction in induced rolling moment on the trailing wing model was realized at a spoiler deflection of about 45 degrees.

Crouch, J.

"AIRPLANE TRAILING VORTICES AND THEIR CONTROL"

C. R. Physique, Vol. 6, 2005, pp. 487-499

Airplane trailing vortices are examined under natural and forced conditions. Control strategies are presented, which aim to reduce the potential for severe upsets resulting from encounters with the vortices. These range from passive control, using span-load modifications, up to active control, using control-surface oscillation. Flight-simulator results are used to judge the effectiveness of the different control strategies. Active control is shown to be effective for breaking up the trailing vortices, and for reducing the potential for severe vortex-encounter upsets. Stability theory is used to explain the mechanisms underlying this form of control.

Crouch, J. D.

"INSTABILITY AND TRANSIENT GROWTH FOR TWO TRAILING-VORTEX PAIRS"

J. Fluid Mech., Vol. 350, November 1997, pp. 311-330

The stability of two vortex pairs is analyzed as a model for the vortex system generated by an aircraft in flaps-down configuration. The co-rotating vortices on the starboard and port sides tumble about one another as they propagate downward. This results in a time-periodic basic state for the stability analysis. The dynamics and instability of the trailing vortices are modelled using thin vortex filaments. Stability equations are derived by matching the induced velocities from Biot-Savart integrals with kinematic equations obtained by temporal differentiation of the vortex position vectors. The stability equations are solved analytically as an eigenvalue problem, using Floquet Theory, and numerically as an initial value problem. The instabilities are periodic along the axes of the vortices with wavelengths that are large compared to the size of the vortex cores. The results show symmetric instabilities that are linked to the long-wavelength Crow instability. In addition, new symmetric and antisymmetric instabilities are observed at shorter wavelengths. These instabilities have growth rates 60-100% greater than the Crow instability. The system of two vortex pairs also exhibits transient growth which can lead to growth factors of 10 or 15 in one-fifth of the time required for the same growth due to instability.

Crouch, J. D.

"STABILITY OF MULTIPLE TRAILING-VORTEX PAIRS"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 17-1 to 17-8

The stability of two vortex pairs is analyzed as a model for the vortex system generated by an aircraft in flaps-down configuration. The co-rotating vortices on the starboard and port sides tumble about one another as they propagate downward. This results in a time-periodic basic state. The instabilities are periodic along the axes of the vortices with wavelengths that are large compared to the size of the vortex cores. The results show symmetric instabilities that are linked to the long-wavelength Crow instability. In addition, new symmetric and antisymmetric instabilities are observed at shorter wavelengths. These instabilities have growth rates 60-100% greater than the Crow instability. The system of two vortex pairs also exhibits transient growth which can lead to growth factors of 5 or 10 in one fourth of the time required for the same growth due to instability.

Crouch, J. D.

"INSTABILITY AND TRANSIENT GROWTH FOR TWO TRAILING-VORTEX PAIRS"

AIAA Paper No. 1997-0062, Reno, NV, January 1997

Two trailing-vortex pairs are studied as a model for the vortex system generated by an aircraft in a flaps-down high-lift configuration. The co-rotating vortices on the starboard and port sides tumble about one another as they propagate downward. This results in a time-periodic basic state for the stability analysis. The dynamics and instability of the trailing vortices are modeled using thin vortex filaments. Stability equations are derived by matching the induced velocities from Biot-Savart with kinematic equations obtained by temporal differentiation of the vortex position vectors. The stability equations are solved analytically as an eigenvalue problem, using Floquet theory, and numerically as an initial value problem. The instabilities are periodic along the axes of the vortices with wavelengths that are large compared to the size of the vortex cores. The results show symmetric instabilities that are linked to the long-wavelength Crow instability. In addition, new symmetric and antisymmetric instabilities are observed at shorter wavelengths. These instabilities have growth rates 60-100% greater than the Crow instability. The system of two vortex pairs also exhibits transient growth which can lead to growth factors of 5 or 10 in one-fourth of the time required for the same growth due to instability.

Crouch, J. D.

"FORCING THE BREAKUP OF AIRPLANE TRAILING VORTICES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Boeing is working to develop an active system to break up the trailing vortices within a prescribed distance that is less than some current airplane separation distances. Airplane control surfaces are used to force flaps-down vortex instabilities that lead to the breakup of the vortices into vortex rings. The concept has been tested in a towing tank using a simplified flaps-down model. Breakup into vortex rings was achieved with a moderate level of forcing at a distance of about 2.5 to 3 nmi. behind the airplane (when scaled to flight for a 747 airplane). The experimental results are in general agreement

with numerical simulations. The performance of the active system depends on details of the airplane configuration (e.g., the flap system and horizontal tail loading). Ongoing efforts are aimed at determining a simple set of parameters that can be used to predict the effectiveness of the system for a given configuration. Before such a system can be implemented, there are a number of issues that must be addressed. These issues can be grouped into active-airplane issues, following-airplane issues, and airport-environment issues. The most obvious issues for the active airplane are the potential impact on ride quality, dynamic-load effects on the structure, and the ability to maintain control authority during operation. In terms of the following airplane, the primary question is at what stage in the breakup can the vortices be considered benign. Airport-environment issues include determining how the breakup is affected when the vortices are near the ground, what are the effects of atmospheric stratification and shear winds, and how can the total system reliability be demonstrated to such a high level that rules can be changed.

Crouch, J. D. and Czech, M. J.

"ASSESSING WAKE TURBULENCE CHARACTERISTICS FOR COMMERCIAL AIRCRAFT"

AIAA Paper 2016-3133, June 2016, Washington, DC.

The strength of trailing vortices at distances of following aircraft has become a key metric for assessing safe separations between aircraft in the airport terminal area. Different methods for determining wake strength are discussed and compared. A computational fluid dynamics approach is described in detail, consisting of an initialization stage and an evolution stage. The initialization is based on a full-configuration analysis as would be done for assessing the airplane configuration performance. The wake evolution takes advantage of quad-three-dimensional approximations resulting in greater efficiency, which allows the simulation of the wake to times equivalent to several miles behind the aircraft. Both initialization and wake evolution results are shown to be in good agreement with wind-tunnel measurements in the near field. The far-field wake simulations are found to be in good agreement with flight data for some of the key metrics governing the far-field wake strength.

Crouch, J. D. and Spalart, P. R.

"ACTIVE SYSTEM FOR EARLY DESTRUCTION OF TRAILING VORTICES"

Patent 6,082,679, 4 July 2000, Boeing Company, Seattle, WA

An active control method and apparatus for encouraging the early destruction of trailing vortices formed by a lifting body having at least two control surfaces on each side and creating multiple vortex pairs is provided. The method includes actuating the control surfaces in a manner leading to the direct excitation of one or more of the Transient Growth Mechanism, the Short Wavelength Instability, the Long Wavelength Instability, and the Crow Instability to result in the accelerated breakup of the trailing vortices. A method of selecting control parameters in an active control system includes identifying the near-field vorticity distribution of the aircraft, selecting at least one amplification mechanism for

distorting the trailing vortices, determining amplitudes and wavelengths for imposed vortex perturbations, simulating trailing vortex evolutions, determining effectiveness of perturbations and amplification mechanisms, determining vortex positions as a function of control surface deflections, and determining control parameters to govern the movement of the wing control surfaces.

Crouch, J. D., Miller, G. D. and Spalart, P. R.

"ACTIVE-CONTROL SYSTEM FOR BREAKUP OF AIRPLANE TRAILING VORTICES"

AIAA Journal, Vol. 39, No. 12, December 2001, pp. 2374-2381

Wing control surfaces are used to trigger the breakup of trailing vortices behind aircraft in a flaps-down configuration. In the near field of the aircraft there are multiple pairs of vortices, which admit new instability mechanisms that do not exist on a single pair of vortices. A periodic motion of the control surfaces is used to introduce a unique form of perturbation that is amplified in the multiple vortex-pair system but conserves total circulation, lift, and rolling moment. Growth of the perturbations leads to the periodic pinching of the starboard and port vortices into a series of vortex rings. The concept is demonstrated using numerical simulations and towing-tank experiments. Results show that the system breaks up the trailing vortices more rapidly than a comparable excitation of the Crow instability on a single pair of vortices. The overall effectiveness of the system depends on the airplane configuration, namely, details of the flap system and the horizontal tail.

Crouch, J., Miller, G. and Spalart, P.

"DEVELOPMENT OF AN ACTIVE SYSTEM TO BREAK UP TRAILING VORTICES BEHIND COMMERCIAL AIRPLANES"

Boeing Aero, April 2001, pp. 24-31

Boeing is developing a system that shows promise for breaking up trailing vortices behind flaps-down commercial airplanes within distances less than some current approach separations. The system uses control surfaces to cyclically shift a small fraction of the lift between inboard and outboard sections of the wing to trigger wake instabilities that destroy the vortices. The system has been demonstrated in ground-based testing, but outstanding technical issues are still being addressed and the system must be validated in flight. Along with continued technical success, future development and use of the system will require broad industry and regulatory support.

Crow, S. C.

"STABILITY THEORY FOR A PAIR OF TRAILING VORTICES"

D1-82-0918, September 1969, Boeing Scientific Research Laboratories, Seattle, WA.

Trailing vortices do not decay by simple diffusion. Usually, they undergo a symmetric and nearly sinusoidal instability, until eventually they join at intervals to form a train of vortex rings. The theory

accounts for the instability during the early stages of its growth. The vortices are idealized as interacting lines; their core diameters are considered by a cut-off in the line integral representing self-induction. The equation relating induced velocity to vortex displacement gives rise to an eigenvalue problem for the growth rate of sinusoidal perturbations. Stability is found to depend on the products of vortex separation (b) and cut-off distance (d) times the perturbation wavenumber. Depending on those products, both symmetric and antisymmetric eigenmodes can be unstable, but only the symmetric mode involves strongly interacting long waves. An argument is presented that $d/b = 0.07$ for the vortices trailing from an elliptically loaded wing.

Crow, S. C.

"STABILITY THEORY FOR A PAIR OF TRAILING VORTICES"

AIAA Journal, Vol. 8, No. 12, December 1970, pp. 2172-2179

Trailing vortices do not decay by simple diffusion. Usually, they undergo a symmetric and nearly sinusoidal instability, until eventually they join at intervals to form a train of vortex rings. The present theory accounts for the instability during the early stages of its growth. The vortices are idealized as interacting lines; their core diameters are considered by a cutoff in the line integral representing self-induction. The equation relating induced velocity to vortex displacement gives rise to an eigenvalue problem for the growth rate of sinusoidal perturbations. Stability is found to depend on the products of vortex separation b and cutoff distance d times the perturbation wavenumber. Depending on those products, both symmetric and antisymmetric eigenmodes can be unstable, but only the symmetric mode involves strongly interacting long waves. An argument is presented that $d/b = 0.063$ for the vortices trailing from an elliptically loaded wing. In that case, the maximally unstable long wave has a length $8.6b$ and grows by a factor e in a time $9.4(AR/CL)$ times (b/V) , where AR is the aspect ratio, CL is the lift coefficient, and V is the speed of the aircraft. The vortex displacements are symmetric and are confined to fixed planes inclined at 48° to the horizontal.

Crow, S. C.

"MOTION OF A VORTEX PAIR IN A STABLY STRATIFIED FLUID"

Research Report No. 1, May 1974, Poseidon Research, Santa Monica, CA

A theory is developed for the descent of a vortex pair in a stably stratified fluid. The stratification is assumed to be weak, and the evolution of vorticity is traced without recourse to assumptions about turbulent mixing. The conclusion is that the vortices draw together and accelerate downward under the influence of stable stratification, contrary to the intuition that the recirculation cell might buoy upward. Fluid particles do rebound to their original levels, but in the form of a buoyant upwash above a diminishing cell. Eventually the vortex cores overlap, and their impulse radiates away on internal waves.

Crow, S. C.

"STABILITY THEORY FOR A PAIR OF TRAILING VORTICES"

AIAA Paper No. 1970-0053, NY, January 1970

Presents a theory to find the cause of the instability of the pair of contra-rotating vortices that trail behind an aircraft. The persistence of coherent flow depends mainly on the growth rate of the instability that precedes the formation of vortex rings. Investigates the growth rate of this instability.

Crow, S. C. and Bate, Jr., E. R.

"LIFESPAN OF TRAILING VORTICES IN A TURBULENT ATMOSPHERE"

Journal of Aircraft, Vol. 13, No. 7, July 1976, pp. 476-482

The lifespan of aircraft trailing vortices is controlled by a mutual induction instability excited by atmospheric turbulence. The instability itself is well understood. The purpose here is to incorporate the effects of turbulence and thereby predict wake lifespan as a function of meteorological conditions. Eddies of the relevant size are assumed to lie in the Kolmogorov inertial subrange. A statistical definition of lifespan is proposed. The paper concludes with a review of a practical method for actively exciting the mutual induction instability. The method would shorten the typical lifespan of a 747 wake by a factor of 3.

Crowder, J. P.

"SMOKE FLOW VISUALIZATION IN LARGE INDUSTRIAL WIND TUNNELS"

9th International Symposium on Flow Visualization, Paper No. 69, 2000, pp. 69-1 - 69-10

The use of smoke in visualizing features of an aerodynamic flow field is often regarded as one of the most prominent applications in the field of flow visualization. However, the use of smoke flow visualization in large industrial wind tunnels is problematical due to practical difficulties of producing the smoke in the required quantity and location. Furthermore, the utility of smoke flow visualization depends very much on the nature of the flow field under study. Flow fields that experience large vortex roll-up features tend to be much more receptive to useful smoke flow visualization applications than do situations with bluff-body-type separation. The Flying Strut traverser has proven to be an important element in the practical application of smoke flow visualization in such settings. The paper includes details of Flying Strut traverser systems, smoke generators and lighting requirements. Several examples of smoke images are examined and ambiguities discussed.

Crowdy, D. and Marshall, J.

"ANALYTICAL SOLUTIONS FOR ROTATING VORTEX ARRAYS INVOLVING MULTIPLE VORTEX PATCHES"

J. Fluid Mech., Vol. 523, 2005, pp. 307-337

A continuous two-parameter family of analytical solutions to the Euler equations are presented representing a class of steadily rotating vortex arrays involving $N + 1$ interacting vortex patches where N is greater than or equal to 3 is an integer. The solutions consist of a central vortex patch surrounded by an N -fold symmetric alternating array of satellite point vortices and vortex patches. One of the parameters governs the size of the central patch, the other governs the size of the N satellite patches. In the limit where the areas of the satellite vortex patches tend to zero, the solutions degenerate to the exact solutions of Crowdy. Limiting states are found in which cusps form only on the central patch, only on the satellite patches, or simultaneously on both central and satellite patches. Contour dynamics simulations are used to check the mathematical solutions and test their robustness. The linear stability of a class of 'point-vortex models' (in which the patches are replaced by point vortices) are also studied to examine the stability of the distributed-vorticity configurations to pure-displacement modes. On the other hand, a desingularization of all point vortices to Rankine vortices leads to a class of 'quasi-equilibria' consisting purely of interacting vortex patches close to hydrodynamic equilibrium.

Crowdy, D. and Marshall, J.

"GROWING VORTEX PATCHES"

Physics of Fluids, Vol. 16, No. 8, August 2004, pp. 3122-3130

This paper demonstrates that two well-known equilibrium solutions of the Euler equations -- the corotating point vortex pair and the Rankine vortex -- are connected by a continuous branch of exact solutions. The central idea is to 'grow' new vortex patches at two stagnation points that exist in the frame of reference of the corotating point vortex pair. This is done by generalizing a mathematical technique for constructing vortex equilibria first presented by Crowdy [D. G. Crowdy, 'A class of exact multipolar vortices' Phys. Fluids 11, 2556 (1999)]. The solutions exhibit several interesting features, including the merging of two separate vortex patches via the development of touching cusps. Numerical contour dynamics methods are used to verify the mathematical solutions and reveal them to be robust structures. The general issue of how simple vortex equilibria can be continued continuously to more complicated ones with very different vortical topologies is discussed. The solutions are examples of exact solutions of the Euler equations involving multiple interacting vortex patches.

Crozon, C., Steijl, R. and Barakos, G. N.

"NUMERICAL STUDY OF HELICOPTER ROTORS IN A SHIP AIRWAKE"

Journal of Aircraft, Vol. 51, No. 6, November-December 2014, pp. 1813-1832.

Operating helicopters in a naval environment is challenging because it imposes a pilot workload significantly higher than that during land-based operations. The aerodynamic interaction between the aircraft and the ship wake is known to play an important role in increasing the pilot workload, hence reducing the aircraft capability because of the need to maintain safety. As a further step toward numerical prediction of ship/helicopter operational limitations, computational-fluid-dynamics

simulations are conducted for the Canadian Patrol Frigate. The effect of the rotor is included in the simulation, first using an actuator-disc method together with steady calculations, then using rotor blades and the unsteady Reynolds-averaged Navier-Stokes equations. Results using the actuator-disc method demonstrate the importance of coupling effects on the wake and rotor inflow when the rotor is operating close to the ship and therefore the invalidity of superposition methods. The case of a Sea King helicopter main rotor hovering above the deck just before touchdown is reproduced to overcome the limitations of steady calculations and the actuator-disc method. Predictions of rotor thrust compare well with the experimental data available and give confidence in the results. The findings highlight the differences in rotor loading between forward flight and near-deck operation. The possibility of using such simulations for determining safe flight envelopes is discussed as part of the future work.

Cuerva, A., Sanz-Andres, A. and Navarro, J.

"ON MULTIPLE-PATH SONIC ANEMOMETER MEASUREMENT THEORY"

Experiments in Fluids, Vol. 34, 2003, pp. 345-357.

In this paper, a model of the measuring process of sonic anemometers with more than one measuring path is presented. The main hypothesis of the work is that the time variation of the turbulent speed field during the sequence of pulses that produces a measure of the wind speed vector affects the measurement. Therefore, the previously considered frozen flow, or instantaneous averaging, condition is relaxed. This time variation, quantified by the mean Mach number of the flow and the time delay between consecutive pulses firings, in combination with both the full geometry of sensors (acoustic path location and orientation) and the incident angles of the mean with speed vector, give rise to significant errors in the measurement of turbulence which are not considered by models based on the hypothesis of instantaneous line averaging. The additional corrections (relative to the ones proposed by instantaneous line-averaging models) are strongly dependent on the wave number component parallel to the mean wind speed, the time delay between consecutive pulses, the Mach number of the flow, the geometry of the sensor and the incidence angles of mean wind speed vector. Kaimals limit $k_{sub W1} = 1/l$ (where $k_{sub W1}$ is the wave number component parallel to mean wind speed and l is the path length) for the maximum wave numbers from which the sonic process affects the measurement of turbulence is here generalized as $k_{sub W1} = (C_{sub l})/l$, where $C_{sub l}$ is usually lesser than unity and depends on all the new parameters taken into account by the present model.

Cuji, E. A., Lukaczyk, T. W. and Garcia, E.

"AIRCRAFT DYNAMICS, WIND TUNNEL TESTING AND CFD FLOW VISUALIZATION OF TWO LINKED UAVS FLYING AT CLOSE PROXIMITY"

Proceedings SPIE, Vol. 7643, Active and Passive Smart Structures and Integrated Systems, April 2010, pp. 76432C-1 - 76432C-12.

This paper presents an analysis of close-proximity aerodynamics and aircraft dynamics of two Linked UAVs. As the UAVs approach each other for wingtip docking there will be strong aerodynamic coupling between their wing tips. Lifting line and Computational Fluid Dynamics (CFD) simulation as well as wind tunnel testing of close-proximity effects on lift, drag, roll, pitch and yaw moments for two UAV wings has been performed. The proximity aerodynamics effects between the UAVs wings were analyzed as a function of its relative position in all three directions. A look-up library of aerodynamic forces and moments for relative positions and angles of attack between the two UAVs has been developed. In this study we examined how the close-proximity aerodynamics affects the dynamics and stability of the UAVs. The aircraft dynamics analysis is done in Simulink, which will include the close-proximity aerodynamic look-up library. An aerodynamic disturbance intensity field will be generated, utilizing both simulation and wind tunnel data, to determine a trajectory for the two UAVs to approach each other for docking.

Cummings, J. L. and Haefeli, R. C.

"DOWNWASH IN VORTEX REGION BEHIND RECTANGULAR HALF-WING AT MACH NUMBER 1.91"

NACA RM-E50H10, October 1950, Langley Aeronautical Lab., Langley Field, VA

The results of an experimental investigation to determine the downwash in the region of the trailing vortex system behind a rectangular half-wing in a supersonic stream are presented. The half-wing had an aspect ratio of 1.667, a 5-percent-thick symmetrical diamond cross section, and was beveled to a knife edge at the tip. The investigation was made at a Mach number of 1.91 and a Reynolds number of 1,560,000 based on the wing chord. A wake survey was also conducted. At small angles of attack, the experimental spanwise variation generally followed the trends indicated by linearized theory based on the assumption that the trailing vortex sheet was undistorted. At higher angles of attack, the downwash field was greatly influenced by the rolling up of the vortex sheet. At each chordwise station the downwash field progressively changed with increasing angle of attack from that induced by an undistorted vortex sheet toward that induced by a completely rolled-up vortex sheet. The form and the location of the vortex sheet was indicated by a wake survey.

Cummings, J. L., Mirels, H. and Baughman, L. E.

"DOWNWASH IN VORTEX REGION BEHIND TRAPEZOIDAL-WING TIP AT MACH NUMBER 1.91"

NACA RM E9H15, November 1949, Lewis Flight Propulsion Laboratory, Cleveland, OH.

The results of an experimental investigation to determine the downwash in the region of the trailing vortex system behind a trapezoidal-wing tip in a supersonic stream are presented. The wing was cut along the inner Mach line from the tip and had a 5-percent-thick symmetrical diamond cross section. The investigation was made at a Mach number of 1.91 and a Reynolds number of 1,560,000 based on the wing chord. A wake survey was also made.

Cummings, J. L., Mirels, H. and Baughman, L. E.

"DOWNWASH IN VORTEX REGION BEHIND TRAPEZOIDAL-WING TIP AT MACH NUMBER 1.91"

NACA RM E9H15, November 1949, Lewis Flight Propulsion Laboratory, Cleveland, OH.

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Cummings, R. M. and Sandlin, D. R.

"MEASUREMENT AND PREDICTION OF FREE FLIGHT WING-INDUCED VORTEX VELOCITY FIELDS"

AIAA Paper No. 1987-2497, Monterey, CA, August 1987

An experimental method was developed to measure the wing-induced vortex velocity field of a free flight aircraft. Radio-controlled airplane models were flown through a field of small particles and measurements of the particle velocities were made using various photographic techniques. A theoretical model of the motion of the particles was developed and used to determine the vortex strength and velocity field induced by the aircraft. The experimental method is considered for application to full-scale aircraft or for comparisons and analysis of various wingtip vortex alleviation devices.

Curran, P.

"WINGTIP TURBINES FOR VORTEX ALLEVIATION"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 52-1 - 52-19

It has been shown that the strength of a vortex can be alleviated by installing a vortex turbine at the trailing edge of a wingtip. The initial interest in the vortex turbine, however, was not in the area of vortex alleviation. The vortex turbine concept was first investigated as a potential means of producing power and reducing aircraft drag. Power can be generated by taking advantage of the high-speed rotational flow that is present near the core of the vortex. By properly placing a vortex turbine within the high intensity vortex core, rotational energy can be extracted for use in secondary power applications onboard the aircraft. The rotational energy can be converted to electrical, hydraulic, pneumatic, or a combination of these modes of power. The unique feature of the vortex turbine in generating power is that it extracts power from the rotational flow rather than from the free-stream velocity component; the free stream flow is not utilized and the drag penalties associated with extracting power from the free stream are avoided. It has been demonstrated in both wind tunnel tests and small-scale flight tests that the vortex turbine can reduce the induced drag of an aircraft by disrupting the formation of the vortex. During flight the vortex exerts an upward flow component outboard of the wing tips, and a downward component directly behind the wing. This downward component, or downwash, contributes to the induced drag of an aircraft, and can be reduced by locating the vortex turbine in the center of the vortex flow field where the rotational velocities are greatest. The vortex turbine hinders the formation of the vortex, and can reduce the induced drag of the wing by as much as 20 percent.

Currin, H. D., Cotton, F. N. and Wood, B.

"DYNAMIC PRESCRIBED VORTEX WAKE MODEL FOR AERODYN"

AIAA Paper No. 2007-421, Reno, NV, January 2007

A new aerodynamic model has been developed for Horizontal Axis Wind Turbines. The prescribed vortex wake code HAWTDAWG, developed at the University of Glasgow, has been extended for dynamic flow conditions. The new model is built into the aerodynamic code AeroDyn and linked to the structural dynamics code FAST. The new model has been validated using Unsteady Aerodynamic Experiment Phase VI wind tunnel axial flow data. Comparisons are made to Blade Element Momentum and Generalized Dynamic Wake models.

Curry, R. E.

"UTILIZATION OF THE WING-BODY AERODYNAMIC ANALYSIS PROGRAM"

NASA-TM-72856, October 1978, NASA Dryden Flight Research Center, Edwards, CA

The analysis program was used to investigate several aircraft characteristics. The studies performed included vehicle stability analysis, determination of upwash angle, identification of nonpotential flow, launch dynamics, and wake vortex upset loads. The techniques are discussed and when possible, computed results are compared with experimental data.

Curtiss Jr., H. C. and Zhou, Z.

"FURTHER STUDIES OF THE RESPONSE OF SINGLE ROTOR HELICOPTERS TO VORTEX ENCOUNTERS"

Technical Report MAE-1726, Sept. 1985, Princeton University, Princeton, NJ.

A simplified approach to the problem of controlling the response of a helicopter in an encounter with the trailing vortex of a large transport aircraft indicates the following: 1) The uncontrolled longitudinal motions of a helicopter induced by the vortex field are of large amplitude. The effectiveness of a simple attitude feedback tends to indicate that it should be relatively easy for the pilot to suppress the longitudinal motion. 2) The roll of the helicopter can be suppressed by lateral control feedback; however, this feedback does little to suppress the yawing motion. 3) Directional control feedback suppresses the yawing motion but on two of the helicopters tends to amplify the rolling motion. The effectiveness of the yaw suppression is sensitive to pilot lags. 4) The nature of these results indicating that suppression of the lateral-directional motion is clearly a multi-loop task and sensitive to pilot time lags indicates that pilot-in-the-loop simulation experiments are highly desirable.

Curtiss Jr., H. C. and Zhou, Z.-g.

"THE DYNAMIC RESPONSE OF HELICOPTERS TO FIXED WING AIRCRAFT WAKE ENCOUNTERS"

Proceedings of the Theoretical Basis of Helicopter Technology Seminar, American Helicopter Society, November 1985, Alexandria, VA.

Fixed wing aircraft may experience a severe upset if they encounter the trailing vortex of a large jet transport. Limited flight experiments using a teetering rotor helicopter indicate that the response of a helicopter to a trailing vortex encounter is considerably less severe. This paper considers the basic nature of the gust response of helicopters and presents a simplified analytical approach to the problem of predicting the response of a single rotor helicopter to trailing vortex encounter. Consideration is given to the estimation of main rotor flapping as well as the motion of the complete vehicle. The influence of helicopter configuration, main rotor type and helicopter size relative to the vortex on the response is discussed and illustrated by calculation of the dynamic response of various helicopters to an encounter with the trailing vortex of a large transport aircraft. Results are compared to flight test. Basic reasons for the difference in severity of the response of fixed wing aircraft compared to helicopters are discussed.

Curtiss, Jr., H. C. and Zhou, Z.

"THE RESPONSE OF HELICOPTERS TO FIXED WING AIRCRAFT WAKE ENCOUNTERS"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 14-1 - 14-23

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nature of the gust response of helicopters and presents a simplified analytical approach to the problem of predicting the response of a single rotor helicopter to trailing vortex encounter. Consideration is given to the estimation of main rotor flapping as well as the motion of the complete vehicle. The influence of helicopter configuration, main rotor type and helicopter size is discussed and illustrated by calculation of the dynamic response of various helicopters to an encounter with the trailing vortex of a large transport aircraft. Results are compared to flight test. Basic reasons for the difference in severity of the response of fixed wing aircraft compared to helicopters are discussed.

Curtiss, Jr., H. C. and Zhou, Z.

"A PRELIMINARY STUDY OF THE RESPONSE OF SINGLE ROTOR HELICOPTERS TO VORTEX ENCOUNTERS"

MAE-1699, April 1985, Princeton Univ., Princeton, NJ.

The results of a preliminary study of the response of a single rotor helicopter to the gust field associated with the wing tip vortex of a large transport aircraft are presented. Consideration is given to the influence of rotor hub type (see-saw, articulated with offset, and hingeless) on the flapping and uncontrolled dynamics response of a helicopter to this gust field.

Curtiss, Jr., H. C., Putman, W. F., and Hanker, Jr., E. J.

"ROTOR AERODYNAMICS IN GROUND EFFECT AT LOW ADVANCE RATIOS"

ARO-16061.2-EG, Princeton University, Princeton, NJ, July 1982

The results of an experimental study of the aerodynamic characteristics of a helicopter rotor operating in ground effect at low advance ratios are presented. Flow visualization studies were conducted along with measurement of the forces and moments acting on the rotor as a function of advance ratio, height above ground and collection pitch. Steady state experiments as well as non-steady experiments involving translational acceleration were conducted. Three distinct flow regimes were noted from the flow visualization studies. At the low end of the advance ratio range a recirculating flow was present, at intermediate advance ratios a horseshoe shaped vortex formed under the rotor, and at the high end of the advance ratio range studied, the rotor wake flows entirely downstream. At test conditions where the recirculating flow or ground vortex is present there are marked departures from classical ground effect theory. Translational acceleration was found to have a significant effect on the rotor forces and moments indicating that some appreciable time is required for the establishment of the ground effect flow field when a recirculating flow or ground vortex exists in the steady state. The results indicate that magnitude of the ground effects experienced by a helicopter are sensitive to the flight path of the helicopter.

Cutler, A. D. and Levey, B. S.

"VORTEX BREAKDOWN IN A SUPERSONIC JET"

AIAA Paper No. 1991-1815, June 1991, Honolulu, Hawaii.

There has been considerable study of vortex breakdown in low-speed flows, but very little is known about it at supersonic speeds. The phenomena is potentially of importance in scramjet fuel mixing applications. In the current study a supersonic vortical jet was created by tangential injection and acceleration through a convergent-divergent nozzle. Vortex circulation was varied and the jet was visualized using Rayleigh scattering from a laser light sheet and focusing schlieren. The results show that the vortical jet mixed much more rapidly with the ambient air than a comparable straight jet. When overexpanded, the vortical jet exhibited considerable unsteadiness and evidence was obtained which suggested vortex breakdown.

Cutler, A. D., Levey, B. S. and Kraus, D. K.

"AN EXPERIMENTAL INVESTIGATION OF SUPERSONIC SWIRLING JETS"

AIAA Paper No. 1993-2922, July 1993, Orlando, FL.

The addition of swirl to scramjet fuel jets has been proposed as a method of enhancing fuel mixing, but little of a fundamental nature is known about supersonic swirling flows. This is a study of mixing in supersonic swirling air jets created by tangential injection and acceleration through a convergent-divergent nozzle into stagnant air. Several cases with different vortex circulations were investigated using pitot, cone and total-temperature probes, and Rayleigh scattering from a laser light sheet. The results show that tangential injection is an efficient method for generating swirling jets; and that when overexpanded, considerable turbulence and increased mixing is created as a result of vortex breakdown.

Cuypers, Y., Maurel, A. and Petitjeans, P.

"COMPARISON BETWEEN AN EXPERIMENTAL TURBULENT VORTEX AND THE LUNDGREN VORTEX"

Journal of Turbulence, Vol. 5, 2004, pp. 1-22

In a recent letter the authors presented experimental results on a structure resulting from a vortex burst. The temporal evolution of this structure results in the k to $-5/3$ power Kolmogorov spectrum and some common features with the Lundgren theoretical vortex have been shown. The purpose of the present paper is to go further in the comparison with the Lundgren model by a parallel analysis of the experimental structure and of a Lundgren single spiral vortex, whose evolution is numerically obtained based on the calculations of Pullin et al.

Czech, M. J., Miller, G. D., Crouch, J. D. and Strelets, M.

"NEAR-FIELD EVOLUTION OF TRAILING VORTICES BEHIND AIRCRAFT WITH FLAPS DEPLOYED"

AIAA Paper No. 2004-2149, Portland, OR, June-July 2004

The near-field development of trailing vortices behind flaps-down airplane configurations is investigated experimentally and numerically. Wind-tunnel wake surveys are measured at the tail of the airplane, and are utilized to initialize the calculations. Downstream surveys (up to ten spans) and flow visualizations from a towing tank are used to characterize the mid-field vortex system. Computational Fluid Dynamics (CFD) results are based on the solution of quasi-3D Reynolds Averaged Navier-Stokes (RANS) equations with a one-equation turbulence model. The inclusion of turbulent-mixing effects is found to be essential to capturing the correct near-field development for realistic vortex systems including a body wake. Results show that wing loadings typical of commercial airplanes in a landing configuration can lead to multiple vortex pairs, or a single vortex pair, in the mid field at say, fifteen spans downstream. The CFD results are shown to be in very good agreement with experimental wake-survey results out to ten spans (the downstream limit for the survey results). The CFD approach is used to calculate mid-field parameters, such as circulation ratios and vortex separation distances, for use in assessing active schemes for breaking up the trailing vortices.

Czech, M., Miller, G., Crouch, J. and Strelets, M.

"PREDICTING THE NEAR-FIELD EVOLUTION OF AIRPLANE TRAILING VORTICES"

C. R. Physique, Vol. 6, 2005, pp. 451-466

The near-field (up to about 20 spans) development of trailing vortices is investigated experimentally and numerically. Computational Fluid Dynamics (CFD) results are based on the solution of quasi-3D Reynolds-averaged Navier-Stokes equations with a one-equation turbulence model. The inclusion of turbulence effects is found to be essential to capturing the correct near-field development. The CFD results are shown to be in very good agreement with experimental wake-survey results out to ten spans. Results show that wing loadings typical of commercial airplanes in a landing configuration can lead to multiple, or single vortex pairs, at distances of fifteen to twenty spans downstream.

D'Errico, R., Hazen, D. A., Rudis, R. P., Spitzer, R. P., and Burnham, D. C.

"A CLIMATOLOGICAL ANALYSIS OF CROSSWINDS AT LOGAN INTERNATIONAL AIRPORT"

Abstract, 10th Conference on Applied Climatology, October 1997, Reno, NV

This paper addresses crosswind and headwind frequency distributions for Logan International Airport, Boston, MA using more than twenty years of hourly surface data archived by the National Climatic Data Center. In addition, based on the same dataset, persistence distributions of crosswind conditions favoring wake vortex transport, retarded movement, or dissipation are evaluated.

Da Silva, C. B., Sousa, J. M. M. and Pereira, J. C. F.

"LARGE-EDDY SIMULATION OF A TRAILING VORTEX SYSTEM BEHIND A CIVIL AIRCRAFT MODEL"

ICAS 1998 Paper 98-2.10.2, Sept. 1998, Melbourne, Australia.

In this paper we investigate Flap-Tip vortex pair interaction behind a civil aircraft model. We perform Large-Eddy Simulation of a pair of Burgers vortices, whose parameters were set according to wind tunnel measurements of a Flap-Tip vortex pair issuing from a civil aircraft model. The study of the isolated (Flap) vortex provides us significant insight about its turbulent structure. In the Flap-Tip vortex system we see how the interaction of the vortices modifies their mean and turbulent flow fields. The work ends with the study of the effect of initial separation distance on the vortex pair development.

Dabas, A., Flament, T., de Bruin, F., Straume, A., Kanitz, T., Reitebuch, O., Marksteiner, U., Huber, D., Isaksen, L., Rennie, M., Stoffelen, A., Marseille, G.-J., de Kloe, J., Lecrenier, O., Lochard, J. and McGoldrick, P.

"ESA WIND LIDAR MISSION AEOLUS"

19th Coherent Laser Radar Conference (CLRC), Paper Mo2, June 2018, Okinawa, Japan.

AEOLUS is a space-based wind lidar. Developed in the frame of the Earth Explorer program of the European Space Agency, it will be launched in late August 2018. Built by Airbus Defence and Space, it will be the first Doppler lidar in space. It will measure winds all over the globe from the surface to the low stratosphere, as well as the optical properties of clouds and aerosols. Its data shall be used for weather and air quality prediction and help better understand the climate of the Earth.

Dabiri, J. O. and Gharib, M.

"FLUID ENTRAINMENT BY ISOLATED VORTEX RINGS"

Journal of Fluid Mechanics, Vol. 511, 2004, pp. 311-331.

Of particular importance to the development of models for isolated vortex ring dynamics in a real fluid is knowledge of ambient fluid entrainment by the ring. This time-dependent process dictates changes in the volume of fluid that must share impulse delivered by the vortex ring generator. Therefore, fluid entrainment is also of immediate significance to the unsteady forces that arise due to the presence of vortex rings in starting flows. Applications ranging from industrial and transportation, to animal locomotion and cardiac flows, are currently being investigated to understand the dynamical role of the observed vortex ring structures. Despite this growing interest, fully empirical measurements of fluid entrainment by isolated vortex rings have remained elusive. The primary difficulties arise in defining the unsteady boundary of the ring, as well as an inability to maintain the vortex ring in the test section sufficiently long to facilitate measurements. We present a new technique for entrainment measurement that utilizes a coaxial counter-flow to retard translation of vortex rings generated from a piston-cylinder apparatus, so that their growth due to fluid entrainment can be observed. Instantaneous streamlines of the flow are used to determine the unsteady vortex ring boundary and compute ambient fluid entrainment. Measurements indicate that the entrainment process does not promote self-similar vortex ring growth, but instead consists of a rapid convection-based entrainment phase during ring formation, followed by a slower diffusive mechanism that entrains ambient fluid into the isolated vortex ring. Entrained fluid typically constitutes 30% to 40% of the total volume of fluid

carried with the vortex ring. Various counter-flow protocols were used to substantially manipulate the diffusive entrainment process, producing rings with entrained fluid fractions up to 65%. Measurements of vortex ring growth rate and vorticity distribution during diffusive entrainment are used to explain those observed effects, and a model is developed to relate the governing parameters of isolated vortex ring evolution. Measurement results are compared with previous studies of the process, and implications for the dynamics of starting flows are suggested.

Daccache, E. and Lee, T.

"EFFECT OF A WINGLET ON NORMAL BLADE-VORTEX INTERACTION"

Journal of Aircraft, Vol. 44, No. 1, January-February 2007, pp. 264-273

The flow field downstream of a blade interacted normally with a winglet-generated double vortex was investigated experimentally. Like the baseline (with no winglet) interaction, the passage of the double vortex over the blade significantly altered the blade circulation distribution, causing negative vorticity to be shed into its wake, which, together with the turbulent wake motions, acted to trigger the turbulent decay of the vortex core, resulting in an increase in its size and loss of circulation. For a junction vortex interacted directly with the blade leading edge, a pair of two counter-rotating vortices, similar to the baseline interaction case, was observed at 1.5 chords downstream of the blade trailing edge. Qualitatively, the variation in double vortex-blade separation distance produced large variations in the vortex core parameters associated with the junction vortex, whereas minor changes for the tip vortex.

Dacles-Mariani, J. and Hafez, M.

"NUMERICAL STUDY OF TIP VORTEX FLOWS"

USGRDR0009, January 2000, University of California, Davis, CA

This paper presents an overview and summary of the many different research work related to tip vortex flows and wake/trailing vortices as applied to practical engineering problems. As a literature survey paper, it outlines the relevant analytical, theoretical, experimental, and computational study found in literature. It also discusses in brief some of the fundamental aspects of the physics and its complexities. An appendix is also included. The topics included in this paper are: 1) Analytical Vortices; 2) Experimental Studies; 3) Computational Studies; 4) Wake Vortex Control and Management; 5) Wake Modeling; 6) High-Lift Systems; 7) Issues in Numerical Studies; 8) Instabilities; 9) Related Topics; 10) Visualization Tools for Vertical Flows; 11) Further Work Needed; 12) Acknowledgements; 13) References; and 14) Appendix.

Dacles-Mariani, J. S., Kwak, D. and Zilliac, G.

"INCOMPRESSIBLE NAVIER-STOKES SIMULATION PROCEDURE FOR A WINGTIP VORTEX FLOW ANALYSIS"

Proceedings of 6th International Symposium on Computational Fluid Mechanics, Lake Tahoe, September 1995, pp. 1-7

The near-field behavior of a wingtip vortex flow has been studied computationally and compared with existing experimental results. The computational approach involved using the method of artificial compressibility to solve the three-dimensional, incompressible, Navier-Stokes equations with experimentally determined boundary conditions. A single grid generation strategy for the wing-wind tunnel wall configuration is outlined. Further, grid density/distribution is given for the vortex core and wing surface requirements. The role of higher-order differencing scheme to approximate the convective terms of the Navier-Stokes equations is discussed. Two one-equation models (Baldwin-Barth turbulence model and Spalart-Allmaras turbulence model) have been used with the production term modified to account for the nearly solid-body rotation effect in the vortex core. Some observations and recommendations, for a simulation procedure will be discussed addressing the impact of solver accuracy, grid resolution/distribution and turbulence modeling on accurate tip vortex flow analysis. Finally, the computed results using 1.5 million grid points is compared with experiment.

Dacles-Mariani, J. S., Kwak, D. and Zilliac, G.

"ACCURACY ASSESSMENT OF A WINGTIP VORTEX FLOWFIELD IN THE NEAR-FIELD REGION"

AIAA Paper No. 1996-0208, Reno, NV, January 1996

Flow prediction of the near-field behavior of a wingtip vortex flow field has been studied and compared extensively with experiment. The computational approach involved using the method of artificial compressibility to solve the three-dimensional, incompressible, Navier-Stokes equations. Two one-equation models (Baldwin-Barth turbulence model and Spalart-Allmaras turbulence model) have been used with the production term modified to account for the stabilizing effect of the nearly solid-body rotation in the vortex core. A grid refinement study using 0.6 million, 1.1 million, 1.5 million and 2.5 million grid points is also presented and discussed. An accuracy assessment study revealed that turbulence modeling errors and errors due to numerics are both important factors which influence the resolution of the tip vortex flow. This study attempts to quantify to what extent each of these two error sources affect the accuracy of tip vortex flow prediction in the near-field.

Dacles-Mariani, J., Hafez, M. and Kwak, D.

"PREDICTION OF WAKE-VORTEX FLOW IN THE NEAR- AND INTERMEDIATE-FIELDS BEHIND WINGS"

AIAA Paper No. 1997-0040, Reno, NV, January 1997

To date, most flow prediction of the wake-vortex flow field model the intermediate-wake where the vortex has been assumed to have completed its roll-up process and is well established. However, it is equally important to accurately predict the near-wake region for improved drag prediction. This study explores the validity of modeling the near- and intermediate wake region behind wings with a simplified Navier-Stokes equations. As possible candidates, the Navier-Stokes equations simplified by invoking the ideal-wake assumption, and using the velocity/vorticity formulation and the stream

function/vorticity formulation were studied. Several acceleration techniques were also investigated including the preconditioned conjugate gradient method. To serve as proof-of-concept, two analytical vortices, the perturbed vortex, and the 3D steady Burgers vortex were investigated. The efficiency and the accuracy of these methods are reported and discussed. Finally, comparison with some measured data are presented. Results of the model equations and of the full Navier-Stokes equations are presented and discussed.

Dacles-Mariani, J., Kwak, D. and Zilliac, G.

"ON NUMERICAL ERRORS AND TURBULENCE MODELING IN TIP VORTEX FLOW PREDICTION"

International J. for Numerical Methods in Fluids, Vol. 30, May 1999, pp. 65-82

The accuracy of tip vortex flow prediction in the near-field region is investigated numerically by attempting to quantify the shortcomings of the turbulence models and the flow solver. In particular, some turbulence models can produce a 'numerical diffusion' that artificially smears the vortex core. Low-order finite differencing techniques of the convective and pressure terms of the Navier-Stokes equations and inadequate grid density and distribution can also produce the same adverse effect. The flow over a wing and the near-wake with the wind tunnel walls included was simulated using 2.5 million grid points. Two subset problems, one using a steady, three-dimensional analytical vortex, and the other, a vortex obtained from experiment and propagated downstream, were also devised in order to make the study of vortex preservation more tractable. The method of artificial compressibility is used to solve the steady, three-dimensional, incompressible Navier-Stokes equations. Two one-equation turbulence models (Baldwin-Barth and Spalart-Allmaras turbulence models), have been used with the production term modified to account for the stabilizing effect of the nearly solid body rotation in the vortex core. Finally, a comparison between the computed results and experiment is presented.

Dacles-Mariani, J., Rogers, S., Kwak, D., Zilliac, G. and Chow, J.

"A COMPUTATIONAL STUDY OF WINGTIP VORTEX FLOWFIELD"

AIAA Paper No. 1993-3010, Orlando, FL, July 1993

The near-field behavior of a wingtip vortex flow is studied computationally using an incompressible flow solver for the Navier-Stokes equations based on the artificial compressibility method. Inaccuracies in current computational studies are addressed, especially, the role of numerical errors and transition/turbulence modeling. A subset problem is devised to make the study of vortex preservation more tractable. As part of the numerical checks, the flow is first run laminar while performing a systematic grid refinement study for the subset problem. Further studies on the numerical errors are conducted with the measured Reynolds stresses introduced into the momentum equations as source terms. As a preliminary study of turbulent flows, the one-equation Baldwin-Barth turbulence model is implemented as well as the approximation of the production term. The full-geometry case is computed using 1.1 million grid points. The results are compared with experiment.

Dacles-Mariani, J., Zilliac, G. G., Chow, J. S. and Bradshaw, P.

"NUMERICAL/EXPERIMENTAL STUDY OF A WINGTIP VORTEX IN THE NEAR FIELD"

AIAA Journal, Vol. 33, No. 9, September 1995, pp. 1561-1568

The near-field behavior of a wingtip vortex flow has been studied computationally and experimentally in an interactive fashion. The computational approach involved using the method of artificial compressibility to solve the three-dimensional, incompressible, Navier-Stokes equations with experimentally determined boundary conditions and a modified Baldwin-Barth turbulence model. Inaccuracies caused by the finite difference technique, grid resolution, and turbulence modeling have been explored. The complete geometry case was computed using 1.5 million grid points and compared with mean velocity measurements on the suction side of the wing and in the near wake. Good agreement between the computed and measured flow fields has been obtained. The velocity distribution in the vortex core compares to within 3% of the experiment.

Dadone, L.

"ROTORCRAFT WAKES IN THE CONTEXT OF AIRPORT OPERATIONS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Helicopters and tiltrotor aircraft are designed for high performance, and low vibration characteristics. Low noise becomes a requirement for civil operation close to urban areas. Rotor wakes play a key role in the flow environment of rotorcraft. The modeling of the interaction between wake and blades is at the core of all rotor aerodynamics and aeroacoustics analysis methods - whether they involve explicit models of the rotor wake, or rely on harmonic representations of rotor inflow characteristics. Dealing with airport environments requires addressing conditions that fall outside of the wake modeling employed in rotor design. Typically, when more rigorous analytical modeling is not possible, empirical data are used to complement the analytical predictions. Progress continues to be made in the modeling of complex flow fields by means of Computational Fluid Dynamics (CFD). Advanced methods are also being investigated to couple flow field information with blade aerodynamics and dynamics effects. This includes, or can potentially include, rotor downwash, ground proximity effects, the interaction of rotorcraft with the wake of large structures and other aircraft, and even blade sailing effects during start-up/shut-down. This presentation will review current rotorcraft analysis methods with emphasis on rotor wake modeling, by both CFD and vortex element methods, addressing what has been done and could be done to deal with flow field issues relevant to airport operations when rotorcraft and fixed-wing aircraft share the space.

Daeninck, G., Cogle, R. and Winckelmans, G.

"LES CALCULATIONS OF SPATIALLY EVOLVING WAKES IN GROUND EFFECT"

AST4-CT-2005-012238, Catholic Univ. of Leuven, Leuven, Belgium, December 2006

The case of a longitudinally developing wake generated by an elliptic wing is investigated at a moderate yet significant Reynolds number, and using LES. The exact same vortex wake is also investigated in a longitudinally uniform configuration (i.e., a temporal simulation with periodic boundary conditions) using the same code and LES sub-grid scale model. Finally, the 2-D (thus necessarily time developing) DNS of the same case is also performed, as a reference. For the two LES, the simulations are performed up to fully developed turbulence. For each configuration, the averaged vorticity field, vorticity fluctuation field, and axial velocity field are presented and discussed. For the 3-D configurations, the flow topology evolution is also analyzed. Finally, the time evolution of diagnostics characterizing the wake dynamics are presented: trajectories, circulation, energy, etc. The results show that, in the initial phase, the flow is essentially two-dimensional. During that phase, the 3-D results match very well with the 2-D reference configuration. One important feature, that is not present in the longitudinally uniform configuration, is the fact that the longitudinally developing wake induces an axial velocity defect in the primary vortices. The longitudinally developing wake therefore exhibits an earlier and more violent transition to turbulence than the longitudinally uniform configuration. The longitudinally developing configuration further differs from the uniform case by the fact that the vortex tubes describe a spiraling motion (i.e., they are not parallel). This feature is suspected to trigger some kind of vortex meandering, only observed in the longitudinally developing configuration.

Daeninck, G., Desenfans, O. and Winckelmans, G.

"SPAN LOADING VARIATIONS AND WAKE ROLL-UP IN GROUND EFFECT"

AST4-CT-2005-012238, Catholic Univ. of Leuven, Leuven, Belgium, September 2006

When an aircraft is close to the ground, its wake is generated in ground effect (IGE). The presence of the ground affects the lift coefficient of the wing section, the span loading of the wing and thus the resulting wake vortex sheet. The roll-up of this vortex sheet is also affected by the presence of the ground. The importance of these effects is here analyzed to determine whether they need to be considered when performing 3-D simulations or when using simplified real-time models. This document addresses the evaluation of span loading and the 2-D numerical simulations of wake roll-up in ground effect. In Section 1, the span loading is evaluated out and in ground effect using a modified 'lifting line' theory. Three cases are considered: an elliptical chord distribution, a uniform chord distribution (rectangular wing) and a double elliptical chord distribution (simplified model of a wing in landing configuration). Four aspect ratios are investigated for each wing, each at five altitudes. Before performing roll-up simulations, the importance of the ground proximity on the lift coefficient of a 2-D airfoil section is studied (Section 2). The span loadings are used to determine the wake initial condition for 2-D roll-up simulations IGE, and the resulting wake vortex system dynamics (Section 3). The effect of the wake generation altitude and the Reynolds number effect are investigated. We essentially analyze the dynamics of a wake generated by an elliptic wing; the case of a double-elliptic wing is also presented.

Daeninck, G., Winckelmans, G. and Jeanmart, H.

"EFFICIENT VORTEX METHODS FOR THE SIMULATION OF THREE-DIMENSIONAL UNSTEADY VORTEX WAKES"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

Vortex wakes that emanate from lifting surfaces (aircraft wings, wind turbine blades, helicopter blades) correspond to trailing vorticity that is spatially compact (sheet-like). For incompressible flows, they can be efficiently simulated using three-dimensional 'vortex element methods'. These methods are Lagrangian (thus accurate for flows dominated by convection) and solve for the vorticity-velocity formulation of the incompressible Navier-Stokes equations. The velocity field (and its gradients) at any point and time is that induced by all vortex elements (particles for free vorticity and boundary elements for bound vorticity): the Biot-Savart law. The use of fast multipole methods and tree codes allows to evaluate those fields very efficiently.

Dafa'Alla, A. A.

"COMPUTATIONS OF THE WAKE VORTICES BEHIND A CIVIL AIRCRAFT HIGH LIFT MODEL"

AIAA Paper No. 2004-1235, Reno, NV, January 2004

FLITE3D was used to compute the flow past a typical high-lift civil aircraft model and the wake region behind it at a Mach number of 0.2. Two flap settings at 32 degrees and 26 degrees were considered, while the slat was deployed at 23 degrees. The computed results predicted the major flow characteristics very well. Comparisons with the experimental data showed good agreement of the locations of the wing tip and flap vortices for the measured lift value. As FLITE3D is an Euler code, the agreement with the vortex strengths was only qualitative. However, all the expected physical trends of the velocity and pressure fields were observed showing that the data could provide useful initialization near-field data to be used in conjunction with any future mid-to-far-field computations with any advanced CFD method. Furthermore, comparisons of the data for the two flap settings with the experimental data supported the approach that viscous effects should be considered as further decambering of the wing. The comparisons also showed that the tip vortex for the 26-degree flap configuration was stronger relative to the flap end one, persisted longer and probably revolved faster round it as compared to that obtained for the 32-degree flap setting. These findings were confirmed by flow animations for the two flap settings.

Daiutolo, H.

"DEVELOPMENT AND EVALUATION OF A WAKE VORTEX ADVISORY SYSTEM"

Proceedings 22nd Annual Meeting, Air Traffic Control Assoc., Las Vegas, NV, October 1977, pp. 155-170

A prototype wake vortex advisory system, presently being tested at Chicago O'Hare International Airport, is examined. The system utilizes a predictive algorithm described by an elliptical boundary drawn about the cross wind and head or tail wind. System testing procedures are outlined noting

simulated and on-site evaluations of procedural implications, capacity gains, delay decreases, reliability, and maintenance. Preliminary results are presented.

Dallmann, U.

"THREE-DIMENSIONAL VORTEX STRUCTURES AND VORTICITY TOPOLOGY"

Fluid Dynamics Research, Vol. 3, 1988, pp. 183-189.

In this paper we describe the formation of steady, three-dimensional flow structures as changes of flow topology. Possible changes are analyzed in the space of divergence-free Navier-Stokes vector fields. Changes occur at structurally unstable flow states, for instance at incipient separation, incipient vortex formation and vortex breakdown, etc. and whenever the flow around a nominally two-dimensional or axisymmetric body becomes three-dimensional. Vortices may be defined as helical flow of fluid particles around a common axis, but we must distinguish between the topological structure of the velocity field and the vorticity field of such vortices (vortical flows). At first, we review our results on near-wall velocity-field structures and then we discuss the topology of the associated vorticity fields. Finally, we develop a geometric description which allows to give a local definition for a three-dimensional vortex based on the invariants of the Jacobian matrix of such Navier-Stokes vector fields.

Dalton, C. and Wang, X.

"THE VORTEX ROLLUP PROBLEM USING LAMB VORTICES FOR THE ELLIPTICALLY LOADED WING"

AIAA Paper No. 1988-3746, Cincinnati, OH, July 1988

The classical roll-up of the vortex sheet trailing the elliptically loaded wing is examined here. Three factors, each of which contributed in a different, yet influential, manner were included in the analysis: use of Lamb vortices as the discrete vortices, use of a variable time step, and a redistribution of the initial vortex discretization as a variant to the traditional equal-spacing or equal-strength models. A smooth spiral roll-up was obtained for dimensionless times which exceed those of all but one previous investigation by at least a factor of ten without an increase in computation time for similar computers. In addition, very good comparison with the results of previous investigators is obtained for similar parameters. The redistribution of the initial discretization was found to prevent an early concentration of vortices in the spiral as the integration occurs. The spiral was found to form with an equal number of turns as in other calculations, but with less tightness which we attribute to the fact that Lamb vortices were used. Double precision arithmetic was necessary to obtain meaningful results.

Dalton, C. and Wang, X.

"THE VORTEX ROLL-UP PROBLEM USING LAMB VORTICES FOR THE ELLIPTICALLY LOADED WING"

Computers & Fluids, Vol. 18, No. 1, 1990, pp.139-150

The classical roll-up of the vortex sheet trailing the elliptically loaded wing is examined. Three factors, each of which contributed in a different, yet influential, manner were included in the analysis: use of Lamb vortices as the discrete vortices, use of a variable time step, and a redistribution of the initial vortex discretization as a variant to the traditional equal-spacing or equal-strength models. The latter two factors are used in the analysis of this problem for the first time in this study. A smooth spiral roll-up was obtained for dimensionless times which exceed those of all but one previous investigator by at least a factor of ten without an increase in computation time for similar computers.

Daly, D. G.

"A LIMITED ANALYSIS OF SOME NONACOUSTIC ANTISUBMARINE WARFARE SYSTEMS"

MS Thesis, March 1994, Naval Postgraduate School, Monterey, CA.

The problem of Anti-Submarine Warfare early in the next century is examined. Non-acoustic detection methods including magnetic anomaly detection, laser radar, and hydrodynamic detection are examined. A simple analysis of their relative effectiveness is made.

Damania, R. B.

"INVESTIGATION OF NEAR FIELD WAKES BEHIND HIGH-LIFT WINGS"

Ph.D. Thesis, 1973, Mississippi State Univ., State College, MS

An experimental study was made of the partially rolled up vortex behind a high lift wing. Specifically, the velocity vector behind a STOL airplane was measured in flight. The data were obtained at two measurement planes behind the wing in the range of 3.0 to 0.85 for flapped and unflapped conditions. Wing surface pressure distribution and wake vorticity were also measured. Results are presented in the form of contour plots of vorticity and velocity components.

Danaila, I.

"VORTEX DIPOLES IMPINGING ON FINITE ASPECT RATIO RECTANGULAR OBSTACLES"

Flow, Turbulence and Combustion, Vol. 72, 2004, pp. 391-406

Numerical simulations of a vortex dipole rebound from finite aspect ratio rectangular obstacles are presented. Compared to the dipole interaction with infinite flat walls studied by Orlandi (Phys. Fluids A2 (1990) 1429) new phenomena are observed. Secondary dipoles formed after the first rebound can undergo head-on collisions and partner exchange. A new lifting dipole is generated, moving in the opposite direction of the initial dipole. This phenomenon occurs for a ratio between the half-width of the obstacle and the dipole radius lower than a critical value depending on the Reynolds number of the flow. Scatter plots show a quasi-linear vorticity-stream function relationship for the lifting dipole. Some passive control strategies to inhibit the generation of lifting dipoles are also suggested.

Daniel, M.

"THE COMPLETE FIRST ORDER EXPANSION OF A SLENDER VORTEX RING"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

Dynamic equations for the axisymmetric part of the velocity field and for the equation of motion of a slender vortex ring are given at first order. This is the correction to the known leading order given by Callegari and Ting. Note that equations to this order are able to describe the evolution of helicity.

Danielian, R., Jorgensen, H. E., Mikkelsen, T., Mann, J. and Harris, M.

"SURFACE-LAYER WIND AND TURBULENCE PROFILING FROM LIDAR: THEORY AND MEASUREMENTS"

EWEC 2006, February 2006, Athens, Greece.

As wind turbines become taller wind energy assessment and turbine control require knowledge of the detailed mean and turbulence wind profiles at bigger heights (150 meters and more). A major challenge for wind power meteorology is therefore to circumvent the traditional role of the tall met-towers by replacing them with equally accurate, but ground-based remote sensing equipment. Compared to wind data from calibrated cup anemometers in tall met-towers, wind data from remote-sensing instrumentation, such as SODARS and LIDARS, still lack precision and data availability compared to met data acquired from a met tower; this is true for use in connection with power curve reference and wind turbine certification purposes. However, recent progress with worldwide optical telecom technology and stable fiber lasers has led to realization of a new and small wind Lidar system named 'ZephIR' able to profile the surface layer up to ~200 meters height. In this paper we describe how improved signal processing has led to more accurate remote wind and turbulence profile measurements. Included in this study, we have furthermore, for the first time to our knowledge, investigated a method to extract turbulence quantities such as the surface friction velocity directly from the LIDARs radial wind measurements. Following a short description of the LIDAR and the applied data processing we compare the LIDAR-retrieved mean wind and friction velocities with corresponding measurements from tall meteorological towers equipped with calibrated cup anemometers and 3D sonic anemometers at heights ranging between 44 meters and 123 meters.

Daniels, T. S.

"SIMULATION OF WAKE VORTEX RADIOMETRIC DETECTION VIA JET EXHAUST PROXY"

Proceedings SPIE 9482, Next-Generation Spectroscopic Technologies VIII, June 2015.

This paper describes an analysis of the potential of an airborne hyperspectral imaging IR instrument to infer wake vortices via turbine jet exhaust as a proxy. The goal was to determine the requirements for an imaging spectrometer or radiometer to effectively detect the exhaust plume, and by inference, the location of the wake vortices. The effort examines the gas spectroscopy of the various major

constituents of turbine jet exhaust and their contributions to the modeled detectable radiance. Initially, a theoretical analysis of wake vortex proxy detection by thermal radiation was realized in a series of simulations. The first stage used the SLAB plume model to simulate turbine jet exhaust plume characteristics, including exhaust gas transport dynamics and concentrations. The second stage used these plume characteristics as input to the Line-By-Line Radiative Transfer Model (LBLRTM) to simulate responses from both an imaging IR hyperspectral spectrometer or radiometer. These numerical simulations generated thermal imagery that was compared with previously reported wake vortex temperature data. This research is a continuation of an effort to specify the requirements for an imaging IR spectrometer or radiometer to make wake vortex measurements. Results of the two-stage simulation will be reported, including instrument specifications for wake vortex thermal detection. These results will be compared with previously reported results for IR imaging spectrometer performance.

Daniels, T. S.

"COMPARISON OF VELOCITY ESTIMATORS FOR WAKE VORTEX DETECTION"

AIAA Paper No. 1999-0516, Reno, NV, January 1999

National Aeronautics and Space Administration researchers are investigating the use of Ka-Band pulsed Doppler radar to detect wing tip generated wake vortices in foul weather conditions. Numerical simulation studies have determined that signal to noise ratios for the radar hardware are expected in the range from 0 to -15 dB. Current methods for estimating Doppler velocity are based on autocorrelation and Fourier analysis. A wavelet-based method is described that relates signed wavelet scaling index to Doppler velocity. Results are derived from the Terminal Area Simulation System and a numerical Doppler radar model. Two schemes for estimating power spectral density coupled with two methods for estimating mean velocity (four different methods altogether) are compared with the wavelet-based method. This new algorithm computes an index and yields a subjective improvement of 6 dB SNR over the other four methods.

Daniels, T. S., Smith, W. L. and Kirev, S.

"RECENT DEVELOPMENTS ON AIRBORNE FORWARD LOOKING INTERFEROMETER FOR THE DETECTION OF WAKE VORTICES"

AIAA Paper No. 2012-2791, June 2012, New Orleans, LA.

A goal of these studies was development of the measurement methods and algorithms necessary to detect wake vortex hazards in real time from either an aircraft or ground-based hyperspectral Fourier Transform Spectrometer (FTS). This paper provides an update on research to model FTS detection of wake vortices. The Terminal Area Simulation System was used to generate wake vortex fields of 3-D winds, temperature, and absolute humidity. These fields were input to the Line-by-Line Radiative Transfer Model, a hyperspectral radiance model in the infrared, employed for the FTS numerical modeling. An initial set of cases has been analyzed to identify a wake vortex IR signature and signature

sensitivities to various state variables. Results from the numerical modeling case studies will be presented. Preliminary results indicated that an imaging IR instrument sensitive to five narrow bands within the 670 to 3150 1/cm spectral region would be sufficient for wake vortex detection. Noise floor estimates for a recommended instrument are a current research topic.

Daniels, T., Smith Sr, W. L. and Kireev, S.

"SIMULATION OF AIRBORNE RADIOMETRIC DETECTION OF WAKE VORTICES"

IEEE Transactions on Geoscience and Remote Sensing, Vol. 53, No. 12, December 2015, pp. 6336-6343.

This paper describes an analysis of the potential of using an airborne Fourier transform spectrometer (FTS) or radiometer to detect wake vortices. The goal was to determine the requirements for an infrared (IR) FTS to effectively detect wake vortices. Initially, a theoretical analysis of wake vortex detection by thermal radiation was realized in a series of simulations. The first stage used the Terminal Area Simulation System (TASS) dynamic model to simulate wake vortex temperature, moisture, and velocity fields. The second stage used these fields as input to the line-by-line radiative transfer model (LBLRTM) to simulate responses from both an imaging IR hyperspectral FTS and an IR imaging radiometer. These numerical simulations generated FTS and radiometer imagery that was compared with the original temperature data. This research supported an effort, using ground-based imaging FTS instruments, to make measurements of wake vortices of various landing aircraft. Results from two different field campaigns have been previously reported. Instrument specifications for wake vortex thermal detection are recommended for an imaging radiometer sensitive within the following two narrow spectral bands: 670-750 1/cm and 2200-2350 1/cm. The instrument must have at the very minimum a noise equivalent differential temperature less than 2 mK and a spectral resolution of at least 32 1/cm.

Danilin, M. Y., Rodriguez, J. M., Ko, M. K. W., Weisenstein, D. K., Brown, R. C., Miake-Lye, R. C. and Anderson, M. R.

"AEROSOL PARTICLE EVOLUTION IN AN AIRCRAFT WAKE: IMPLICATIONS FOR THE HIGH-SPEED CIVIL TRANSPORT FLEET IMPACT ON OZONE"

Journal of Geophysical Research, Vol. 102, No. D17, September 1997, pp. 21,453-21,463

Previous calculations of the ozone impact from a fleet of high-speed civil transports (HSCTs) have been carried out by global two-dimensional (2-D) models which have not included explicit wake processing of sulfur species. This processing could be important for the global sulfate aerosol and ozone perturbations. For an HSCT scenario with emission indices of NO_x and sulfur equal to 5 and 0.4, respectively, and a cruise speed of Mach 2.4, the Atmospheric and Environmental Research (AER) 2-D model gives 0.50-1.1% as the range of the annually averaged O₃ column depletion at 40-50 degrees N. This range is determined by the extreme assumption that emitted SO₂ is diluted into the global model grid box either as gas or as 10 nm sulfate particles. A hierarchy of models is used here to investigate

the impact of processes in the wake on the calculated global ozone response to sulfur emissions by a proposed HSCT fleet.

Dantsker, O. D., Vahora, M., Imtiaz, S. and Caccamo, M.

"HIGH FIDELITY MOMENT OF INERTIA TESTING OF UNMANNED AIRCRAFT"

AIAA Paper 2018-4219, June 2018, Atlanta, GA.

Knowledge of moment of inertia data for an aircraft is critical for both aircraft analysis as well as model development for control. There have been a variety of different methods employed to measure moment of inertia including: physical pendulums, bifilar pendulums, compound pendulums, torsional pendulums, and torque. The accuracy of the moments of inertia determined using these methods depend upon a variety of factors, such as friction, drag, and vibrations. These contributions can be significant, as errors due to drag can increase quadratically with velocity and errors due to friction can increase as mass is added to the system. This paper seeks to build upon previous moment of inertia measurement techniques by considering the effects of drag on experimental measurements. A torque-based moment of inertia testing rig was fabricated in house, made up of a 4 x 6 x 6 ft steel framework and a pulley torque system. The testing rig allows for quick and reliable measurement with minimal error. Validation was performed using a series of bars to quantify how much error is expected and then using a flat plate to demonstrate that drag is negligible. Finally, the testing rig was used to measure the moment of inertia of two unmanned aircraft.

D'Appolito, J. A. and Whitney, D. A.

"LDV WAKE VORTEX DETECTION SYSTEM ASSESSMENT"

TR-6417-1, February 1992, TASC, Reading, MA

This report summarizes the methodology and findings of an engineering evaluation of the Laser Doppler Velocimeter (LDV). The purpose of this effort is to perform an independent technical review of the capability of the LDV to provide quantitative data concerning the location, velocity, size, and strength of aircraft wake vortices. The LDV was evaluated from two perspectives: basic hardware/signal processing capabilities and limitations and post-test data processing procedures. To understand the basic hardware/signal processing characteristics of the system, an analytic LDV simulation was developed and exercised. This simulation captures the major sensor characteristics and its operation, and provides an understanding of what LDV data collection limitations are.

Darmofal, D. L.

"ANALYSIS OF A CONSERVATION LAW MODEL FOR AXISYMMETRIC VORTICES IN PRESSURE GRADIENTS WITH APPLICATIONS TO VORTEX BREAKDOWN"

AIAA Paper No. 1996-0800, Reno, NV, January 1996

A simple hyperbolic conservation law has been analyzed for vortex cores in pressure gradients. In particular, an analogy with quasi one-dimensional compressible flow has been explored; in this analogy shock jumps in the vortex core model equations are assumed to represent axisymmetric vortex breakdown. Using these simple model equations a family of steady vortex core solutions are constructed; the behavior of the vortex cores is determined by the downstream core pressure. One downstream pressure exists for which the flow remains isentropic. Other downstream pressures can result in the formation of steady breakdowns within the domain. The model equations are also compared with axisymmetric Navier-Stokes simulations. For isentropic flows the model and Navier-Stokes results are in good agreement. The model also shows excellent predictive capabilities for the onset of vortex breakdown in the Navier-Stokes simulations.

Darmofal, D. L.

"THE ROLE OF VORTICITY DYNAMICS IN VORTEX BREAKDOWN"

AIAA Paper No. 1993-3036, Orlando, FL, July 1993

The role of vorticity dynamics in vortex breakdown is examined in a theoretical and computational study. Under the assumptions of steady incompressible axisymmetric inviscid flow, a theory is developed concerning the interaction of vortex tilting and stretching in the breakdown process. This analytic theory is then confirmed using an unsteady incompressible axisymmetric viscous flow solver. The theoretical and computational results are in excellent agreement. Both results point towards the importance of vortex tilting in initiating vortex breakdown. The agreement between the inviscid theory and viscous computations indicates that breakdown is primarily an inviscid process. A measure of the susceptibility to breakdown is developed from the inviscid theory which corresponds well with known experimental and numerical trends concerning the occurrence of vortex breakdown.

Darmofal, D. L., Khan, R., Greitzer, E. M. and Tan, C. S.

"VORTEX CORE BEHAVIOUR IN CONFINED AND UNCONFINED GEOMETRIES: A QUASI-ONE-DIMENSIONAL MODEL"

J. Fluid Mechanics, Vol. 449, 2001, pp. 61-84

Axisymmetric vortex core flows, in unconfined and confined geometries, are examined using a quasi-one-dimensional analysis. The goal is to provide a simple unified view of the topic which gives insight into the key physical features, and the overall parametric dependence of the core area evolution due to boundary geometry or far-field pressure variation. The analysis yields conditions under which waves on vortex cores propagate only downstream (supercritical flow) or both upstream and downstream (subcritical flow), delineates the conditions for a Kelvin-Helmholtz instability arising from the difference in core and outer flow axial velocities, and illustrates the basic mechanism for suppression of this instability due to the presence of swirl. Analytic solutions are derived for steady smoothly varying vortex cores in unconfined geometries with specified far-field pressure and in confined flows with specified bounding area variation. For unconfined vortex cores, a maximum far-field pressure rise

exists above which the vortex cannot remain smoothly varying; this coincides with locally critical conditions (axial velocity equal to wave speed) in terms of wave propagation.

Darr, S. T., Morello, S. A., Shay, R. F., Lemos, K. A. and Jacobsen, R.

"A CONSIDERATION OF CONSTRAINTS ON AIRCRAFT DEPARTURE OPERATIONS"

NASA/CR-2009-215763, January 2009, National Institute of Aerospace, Hampton, VA.

This paper presents a system-level perspective on the operational issues and constraints that limit departure capacity at large metropolitan airports in today's air transportation system. It examines the influence of constraints evident in en route airspace, in metroplex operations, and at individual airports from today's perspective and with a view toward future gate-to-cruise operations. Cross cutting organizational and technological challenges are discussed in relation to their importance in addressing the constraints.

Darracq, D. and Corjon, A.

"COMPUTATIONAL INVESTIGATION OF AIRCRAFT TRAILING-VORTEX EVOLUTION IN ATMOSPHERIC BOUNDARY LAYERS"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

This paper presents three-dimensional large eddy simulations (LES) of civil-aircraft trailing vortices in different realistic atmospheric boundary layers (ABL) with a non-hydrostatic meteorological model. These calculations were performed in order to parametrize an operational model aiming at managing the separations between aircraft at take-off and landing. The problems considered here are taken from twelve selected cases corresponding to trials made at Idaho Falls sponsored by the Federal Aviation Administration (FAA) in 1990. During these trials there were two prevalent meteorological conditions: stable boundary layer and turbulent convective boundary layer. The three-dimensional behavior of the wake vortices (Crow instabilities) as well as the effects of the atmospheric parameters (turbulence, lateral wind, stratification) are discussed. The results of the simulations are compared to experimental data.

Darracq, D., Benkenida, A. and Laporte, F.

"NUMERICAL SIMULATIONS OF LARGE AIRCRAFT TYPE WAKES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001.

Numerical simulations may be used for the characterization of aircraft wake vortices in the near to extended near field, i.e. covering downstream distances corresponding to the completion of the roll-up process. Complete aircraft computations enable us to predict the vortex generation mechanisms and the downstream evolution. On the one hand, such simulations appear as an alternative/complement

to wind-tunnel experiments. On the other hand, accurate results in terms of vortex dynamics imply strong numerical requirements, such as high quality meshes (true for both structured and unstructured meshes) and high-order numerical schemes, that allow for steady Euler or Reynolds-averaged Navier Stokes computations (RANS), but not for Large Eddy Simulations (LES) now. Therefore, numerical simulations may usefully benefit from near-field wind-tunnel experiments, used as inlet data for Euler, RANS or LES extended near-field computations. Both approaches corresponding to complete aircraft computations, and to the complementary experimental/numerical approach are presented. The first approach is detailed considering inviscid computations of the flow around a large aircraft type in high-lift configuration by a structured Navier-Stokes solver. Preservation and transport of vorticity being the major concern of the computations, the numerical treatment is described in detail. The second approach is devoted to steady and unsteady simulations of the extended near field of commercial aircraft type wakes from time-averaged experimental data. Steady RANS simulations and LES are compared, confirming the widely-spread assumption of laminar vortex cores surrounded by turbulent fluctuations. The method has been validated against wind-tunnel measurements in the extended near field. Some configuration effects have been investigated, demonstrating the sensitivity of the vortex dynamics in the extended near field with respect to minor configuration changes.

Darracq, D., Corjon, A., Ducros, F., Keane, M. and Buckton, D.

"THREE-DIMENSIONAL NUMERICAL SIMULATION OF WAKE VORTEX DETECTION WITH THE MFLAME 2 MICRON LIDAR"

AIAA Paper No. 1998-0666, Reno, NV, January 1998.

The aim of this paper is to demonstrate that trailing wake vortices can be reliably detected from an axial point of view using Doppler lidar. Three-dimensional large eddy simulations of wake vortices are performed to investigate the performance of an airborne Doppler Lidar based wake vortex detection system, known as the MFLAME system. Three test cases were investigated: i) Crow instabilities, ii) wake vortex decay in isotropic homogeneous turbulence and iii) wake vortex collapse in convective atmospheric boundary layer. In all cases, the axial velocity is not initialized. Once the appropriate flow field is computed, it is inputted into the MFLAME system simulator. The results indicate that a forward-looking Doppler Lidar system can detect wake vortex signatures from several ages of the applied vortices.

Darracq, D., Corjon, A., Ducros, F., Keane, M., Buckton, D. and Redfern, M.

"SIMULATION OF WAKE VORTEX DETECTION WITH AIRBORNE DOPPLER LIDAR"

Journal of Aircraft, Vol. 37, No. 6, November-December 2000, pp. 984-993.

A simulation approach is used to demonstrate that an airborne, forward-looking lidar can detect trailing wake vortices generated by a leading aircraft. Computational fluid dynamics techniques are used to generate flow fields containing wake vortices. These flow fields are applied to a Doppler lidar simulation model. The simulated geometry has the forward-looking lidar mounted on a following

aircraft, whereas the wake vortices are generated by a leading aircraft. In such a configuration, it is not possible to directly detect the strong rotational velocity components of a wake vortex with a Doppler system; detection relies on the presence of induced axial velocity signatures. We demonstrate that axial flows are induced as the vortices evolve, and that these axial flows can be detected with a Doppler lidar system.

Darracq, D., Moet, H. and Corjon, A.

"EFFECTS OF CROSSWIND SHEAR AND ATMOSPHERIC STRATIFICATION ON AIRCRAFT TRAILING VORTICES"

AIAA Paper No. 1999-0985, Reno, NV, January 1999.

This paper presents results of a numerical investigation of atmospheric stratification, crosswind shear and ground friction on aircraft trailing vortices. 2-D direct numerical simulations (DNS) and 3-D large eddy simulations (LES) are performed with, respectively, a high-order Navier-Stokes solver and a non-hydrostatic meteorological simulation system. The results of the simulations are compared to numerical data available in literature and to Idaho Falls experiments. Features of the wake-vortex/shear-layer interaction are evidenced by means of numerous numerical simulations of fundamental test cases. Realistic problems are also investigated demonstrating that, even in non-turbulent ambient field, the 3-D approach may be mandatory in some case in order to represent the collapse of a primary vortex with the secondary one created by ground-friction effect. We also observed that the primary-vortex/secondary-vortex collapse can be canceled by particular crosswind characteristics. Under these conditions the dynamics of the vortices is essentially 2-D preserving the vortex life and increasing hazardous effects for a following aircraft. These calculations were performed to contribute to the parameterization of an operational model aiming at managing the separations between aircraft at take-off and landing.

Das, A. and Wichmann, G.

"ON THE PHYSICS AND KINEMATICS OF VORTEX MOTION IN THE DOWNSTREAM OF A HIGH ASPECT RATIO WING WITH HIGH-LIFT DEVICES"

Aerospace Science and Tech., Vol. 8, 2004, pp. 489-498

Vortical flows, source flows and spiraling flows are very common phenomena in fluid dynamics, as are frequently observed in the field of aerodynamics or atmospheric disturbances. In the present study some analysis is taken up at first on the details of the flow quantities in the core region of the vortical flows, it being the essential part of the vortex, while the surrounding outer region, as accompanying field, retains its usual potential flow character. In case of lifting wings vortex formation at the wing- and flap-edges is a common feature. When high aspect ratio wings with high-lift devices in the landing phase are concerned, they give rise to strong multiple vortices. It is observed that the wing-tip vortex spirals around the stronger flap-edge vortex, with continual decrease of the radial distance between them. Hence, it is essential to analyze the physics and kinematics of such vortex motion. Both

experimental field data and numerical field solutions of such flows are available to compare with the theoretical findings. Based on the causalities of the vortex motion one can work out measures to attenuate such flows downstream of the wing.

Das, D., Bansal, M. and Manghnani, A.

"GENERATION AND CHARACTERISTICS OF VORTEX RINGS FREE OF PISTON VORTEX AND STOPPING VORTEX EFFECTS"

Journal of Fluid Mechanics, Vol. 811, 2017, pp. 138-167.

This paper presents a novel method for generating vortex rings that circumvents some of the drawbacks associated with existing methods in producing them. The predominant effects that occur in previously used methods are due to the presence of some of the other vortices such as the stopping vortex, piston vortex, image vortex and orifice lip generated vortices in the early stage of development. These disturbances influence the geometric, kinematic, and dynamic characteristics of a vortex ring and lead to mismatches with classical theoretical predictions. It is shown in the present study that the disturbance free vortex rings produced follow the classical theory. Flow visualization and particle image velocimetry experiments are carried out in the Reynolds number (defined as the ratio of circulation and kinematic viscosity) range, $2270 < Re < 6790$, to find the translational velocity, total and core circulation, core diameter, ring diameter and bubble diameter. In reference to the earlier studies, significant differences are noted in the variations of the vortex ring diameter and core diameter. A model for the core diameter during the formation stage is proposed. The translational velocity variation with time shows that the second-order accurate formula derived using Hamilton's equation by Fraenkel (J. Fluid Mech., vol. 51, 1972, pp. 119-135) predicts it best.

Dasey, T. J.

"A DEPARTURE WAKE VORTEX MONITORING SYSTEM: CONCEPT AND BENEFITS"

Second USA/Europe Air Traffic Management R&D Seminar, December 1-4, 1998, Orlando, FL

This paper highlights a concept for an automated departure wake vortex separation system. Wake vortex research has focused on reducing aircraft separations on arrival to airports, but in many cases, the departure queues for certain runways are more severely limiting to airport capacity than are arrival constraints. A departure system has the advantages that it could be used in all weather conditions and it is technically simpler because there is no longer a requirement for a 30-minute to several hour weather forecast in order to take advantage of the reduced spacings. This paper examines the technical requirements of such a system, and defines a concept for implementation of the system. An attempt is made to begin to quantify the dollar benefit from a departure system, and the obstacles to implementation of the system are discussed.

Dasey, T. J. and Heinrichs, R. M.

"AN ALGORITHM FOR THE RECOGNITION AND TRACKING OF AIRCRAFT WAKE VORTICES WITH A CONTINUOUS WAVE COHERENT LASER RADAR"

Conference on Coherent Laser Radar, OSA, Keystone, CO, July 1995

A real-time algorithm for localizing and actively following wake vortices is described. Results from an experiment at Memphis airport and from modeled data are discussed. This is the first such system to track vortices, resulting in a more efficient scan and allowing more frequent estimates of location and strength.

Dasey, T. J. and Hinton, D. A.

"NOWCASTING REQUIREMENTS FOR THE AIRCRAFT VORTEX SPACING SYSTEM (AVOSS)"

Proceedings of the 8th Conference on Aviation, Range, and Aerospace Meteorology, Dallas, TX, January 1999

This paper addresses the requirements for the weather portion of AVOSS. The operational decisions that need to be supported are addressed, which helps to define the necessary time scales of the nowcasts. An analysis is presented of meteorological conditions during which an AVOSS would provide capacity enhancement at major U.S. airports. Finally, a discussion of the current understanding of the meteorological variables that affect vortex behavior will be made, including expected accuracy and temporal and spatial resolution.

Dasey, T. J., Campbell, S. D., Heinrichs, R. M., Matthews, M. P., Freehar, R. E., Perras, G. H. and Salamitou, P.

"A COMPREHENSIVE SYSTEM FOR MEASURING WAKE VORTEX BEHAVIOR AND RELATED ATMOSPHERIC CONDITIONS AT MEMPHIS, TENNESSEE"

Air Traffic Control Quarterly, Vol. 5, No. 1, 1997, pp. 49-6.

Models of vortex behavior as a function of atmospheric conditions are being developed to improve safety and minimize unnecessary airport capacity restrictions due to wake vortices. Direct measurements of vortices and the relevant meteorological conditions in an operational setting, which serve to improve the understanding of vortex behavior, are scarce and incomplete. A comprehensive vortex, meteorological, and aircraft measurement system has been constructed at Memphis International Airport and operated in two 1-month periods during 1994 and 1995. A 10.6 micron continuous-wave (CW) coherent lidar was used to measure vortex parameters with high fidelity. This lidar features a number of improvements over previous systems, including an automatic vortex detection and tracking algorithm to ensure efficient scanning. Meteorological data were collected from a 45 m instrumented tower, balloon soundings, a wind profiler/radio acoustic sounding system (RASS),

sonic detection and ranging (SODAR), and other sensors. This paper presents ensemble distributions of the conditions under which the over 500 aircraft were measured, and samples of vortex and atmospheric measurements. These data will be compared with theoretical predictions of vortex behavior as part of the development of an operational system designed to reduce aircraft spacings in the terminal area.

Dasey, T. J., Cole, R. E., Denneno, A. P., Matthews, M. P., Perras, G. H. and Theriault, K. E.

"METEOROLOGICAL MEASUREMENTS AND DATA FUSION FOR THE DALLAS/FT. WORTH (DFW) AIRCRAFT VORTEX SPACING SYSTEM (AVOSS)"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Quebec, Canada, December 1997, pp. 113-117

Since 1994, Lincoln Laboratory has been working under NASA Langley sponsorship to construct a field system for characterizing the atmospheric boundary layer conditions related to vortex behavior. The latest version of this system has been established at Dallas/Ft. Worth (DFW) Airport. The DFW continuous wind measuring instruments include an instrumented 45 m tower and several smaller towers, a radar profiler, two Doppler sodars and two Terminal Doppler Radars. An automated wind data fusion algorithm is used to provide a single headwind and crosswind profile every 5 minutes, with a current vertical resolution of 15 m below 50 m altitude and 50 m resolution from 50 - 600 m. This presentation will outline our view of the meteorological sensing requirements for an arrival vortex advisory system and describe the meteorological instrument layout, data distribution system and wind data fusion algorithm at DFW.

Dasey, T. J., Cole, R. E., Heinrichs, R. M., Matthews, M. P. and Perras, G. H.

"AIRCRAFT VORTEX SPACING SYSTEM (AVOSS) INITIAL 1997 SYSTEM DEPLOYMENT AT DALLAS/FT. WORTH (DFW) AIRPORT"

NASA/L-3, July 1998, MIT Lincoln Laboratory, Lexington, MA

The potential hazard of aircraft encounters with the wake turbulence of preceding aircraft requires the use of minimum separations on landing that are a significant constraint on airport arrival capacity during instrument flight rules (IFR) conditions. The NASA Langley Research Center has been researching the development of the Aircraft Vortex Spacing System (AVOSS) which would dynamically change aircraft arrival separations based on the forecasted weather conditions and vortex behavior. An experimental AVOSS test system has been constructed at DFW airport and includes a large set of meteorological instruments, wake vortex sensors, and an aircraft data collection system. All of this data are relayed to a central processing center at DFW for processing by automated meteorological data fusion algorithms and by NASA vortex behavior prediction software. An initial deployment and test was conducted during a three-week period in September/October of 1997. This document describes the overall system, the Lincoln-deployed sensors, including the Continuous-Wave Coherent lidar, and the meteorological data collection and processing system. Algorithms that were used to process the data

for scientific use are described, as well as the conditions of the data collection and the data format, for potential users of this database.

Dash, S. M. and Kenzakowski, D. C.

"HOT JET/WAKE TURBULENT STRUCTURE AND LASER PROPAGATION: PART I JET/WAKE TURBULENCE MODELING"

21st JANNAF Exhaust Plume Technology Meeting, Vol. 1, Oct. 1994, pp. 59-78.

The prediction of laser propagation through the hot turbulent exhaust of an aircraft (or missile) requires knowledge of the detailed turbulent structure, and in particular, density/temperature fluctuations and inner/outer turbulent scales. The ability to predict the mean flow structure of round turbulent jets in an isolated environment has now become well established including hot jets and supersonic jets. However, the ability to predict density or temperature fluctuations and inner scales is poorly established, as is the ability to predict jet interactions with the aerodynamic vorticity (e.g. with the wing-tip vortex). A three-tier program of work has been in progress to enhance our understanding of the turbulent structure in hot jets and its influence on laser propagation. In Part I of this paper, the turbulence modeling activities will be described whose basis is the new data being generated at NASA LaRC, to be described in Part II of this paper. The k-epsilon turbulence model and 'g' scalar-fluctuation extension have been implemented in this work. The coefficients of the g-equation have been revised in accordance with new temperature fluctuation data for hot, subsonic jets into still air. Data is now being gathered for hot jets in a co-flow which interact with wing-tip vortices. The inclusion of the g-equation into a Navier-Stokes framework and its analysis of this complex jet data for which detailed turbulence statistics will be available will comprise the main part of this paper. The utility of direct numerical simulation (LES approach to be described in paper by Sinha and Dash) to provide additional insight into this complex problem will also be discussed. Part II of this paper discusses the new data, the measurement techniques, and the complexities entailed in data reduction. Part III discusses the military applications (laser countermeasures), new laser propagation data through hot jets (as well as new atmospheric turbulence data, and predictive methodology.

Dash, S. M. and Kenzakowski, D. C.

"TURBULENT ASPECTS OF PLUME AERODYNAMIC INTERACTIONS"

AIAA Paper 95-2373, July 1995, San Diego, CA.

Detailed data on the structure of hot turbulent jets obtained at NASA LaRC has been analyzed using a two-equation modeling approach with extensions. The calculations have been found to be dependent on core turbulence characteristics and the turbulent Prandtl number. Predictions of Mach .24 and Mach .85 hot jets are described and compared with measurements. For realistic aircraft problems, jets are immersed in an aerodynamic flow field and experience complex interactions. Experiments for the interaction of hot jets with wing wake/vortices indicate substantive deflection of the jet and distortion of the round profile which will impact noise emission due to modification of the turbulence

characteristics. Full NS simulations are described and compare quite well with the data. Recent work has entailed the development of specialized pressure-splitting methodology to permit the time-iterative spatial marching analysis of 3D jets with negligible streamwise pressure variations (the cross-plane analysis is fully elliptic). Unit problems for rectangular jets in a uniform stream have been performed and compare favorably with full Navier-Stokes predictions.

Daugherty, J. W.

"STUDY OF THE ELECTROSTATIC FIELD AND CHARGE DISTRIBUTION IN A VORTEX SEEDED WITH DUST"

Ph.D. Thesis, June 1973, Ohio State Univ., Columbus, OH

An experimental program was undertaken to investigate the vortex geometry, particle distribution and electric field distribution in a trailing vortex shed from an airfoil tip placed in a dust laden flow. A differential airfoil, positioned in a subsonic wind tunnel, generated the trailing vortex. Vortex geometry, particle distribution and electric field intensity were measured throughout the plane normal to the wind tunnel axis at several locations downstream from the airfoil.

Davenport, L. H. and Vitalle, R. F.

"A SIMPLIFIED METHODOLOGY FOR THE CATEGORIZATION OF UNMANNED AERIAL VEHICLES"

AIAA Paper 2017-4269, June 2017, Denver, CO.

In this work, a categorization methodology is proposed which allows a relative grouping of Unmanned Aerial Vehicles (UAV) according to sensitivity to wake turbulence using the parameters of operating speed, wing span and Rolling Moment Coefficient (RMC). Potential operating altitudes and corresponding airspeeds for UAV are examined and used as the basis for assigning input parameters used in the calculations. A short form adaptation of the RMC equation is developed that reduced the number of input parameters and simplified the calculation. The categorization of UAVs into three groups using these findings is proposed.

Davenport, L. H., Murphy, S. W. and Johnson, E. J.

"WAKE TURBULENCE MITIGATION USING A STANDARDIZED LATERAL OFFSET PROCEDURE"

AIAA Paper 2018-3190, June 2018, Atlanta, GA.

In this preliminary study, the operation of a Standardized Lateral Offset is analyzed for its application as a wake avoidance procedure at separation distances equal or less than the current 5NM minimum. The procedure is wind dependent and is designed for use in high altitude cruise flight by a pair of aircraft on a defined trajectory which are equipped with a Flight Management Computer and for GNSS navigation. A minimum crosswind to transport wake turbulence is calculated based on aircraft navigation cross track error. The WakeWlse probabilistic modeling tool is also used to investigate if the wake turbulence from an aircraft performing the Standard Lateral Offset could affect a trailing aircraft

on the primary route. The use and content of aircraft derived MET data as a planning and monitoring tool for the flight crew is also discussed.

Davenport, L. H., Vitale, R. F. and Proctor, F. H.

"A PRELIMINARY ANALYSIS AND COMPARISON OF IN-FLIGHT WAKE TURBULENCE DATA"

AIAA Paper 2018-3021, June 2018, Atlanta, GA.

This paper presents an overview and preliminary analysis of wake turbulence data collected behind commercial airliners in high altitude cruise flight. The analysis presented in this research uses a subset of data comprised of four aircraft types in the Heavy and Super weight categories. The spatial location of vortex cores and the derivation of key parameters such as tangential velocity and circulation strength are discussed. Vortex core separation distances and descent profiles with respect to wake age and trail distance are determined by measurement of the lateral position of vortex core centers and the recorded altitudes of the vortex crossings. Estimates of vortex core radius are obtained using a combination of aircraft position and the velocity profiles of wind components measured during vortex crossings. A tangential velocity profile derived from these wind components is also compared in a series of velocity profiles from three idealized vortex models.

Davies, H.

"NATS VOLUNTARY WAKE INCIDENT REPORTING DATABASE: DESCRIPTION AND USES"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

This presentation describes the NATS Database of voluntarily reported wake vortex incidents. This will include outlining the process by which reports are captured for pilots and ATC, and also the information gained from other sources (met/radar data). Examples are given of how this data is analyzed and presented for an annual UK Wake Vortex performance report (although due to commercial sensitivity it is not possible to report numbers). The presentation will also suggest a potential methodology for calculating wake vortex separations for new spacing categories from historical data (i.e. for categories for which no current data exists.).

Davies, H.

"THE S-WAKE VORTEX INCIDENT DETECTION AND DATA COLLECTION"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

This presentation includes a summary of the work undertaken by NATS in the S-Wake Project. This includes: Validation of the NLR-Vortex Algorithm; Analysis of Preliminary Wake Vortex Encounters

detected from Flight Data Recorder (FDR) data by algorithm; and Analysis of Pilot reported Wake Vortex Encounters.

Davis, S. S.

"THEORY OF DISCRETE VORTEX NOISE"

AIAA Journal, Vol.13, No. 3, March 1975, pp. 375-380.

A solution is obtained for the noise induced by vortex shedding from the trailing edge of a semi-infinite flat plate. The solution for the potential flow is based on a procedure whereby an inner incompressible flow is matched to an outer acoustic field. Acoustic wave fronts are calculated and compared qualitatively with Schlieren photographs of similar flows. The acoustic directivity pattern is obtained, and the extreme sensitivity of this parameter to the incompressible flow near the trailing edge of the plate is investigated.

Davis, T.

"THE MEASUREMENT OF DOWNWASH AND SIDEWASH BEHIND A RECTANGULAR WING AT A MACH NUMBER OF 1.6"

Journal of the Aeronautical Sciences, Vol. 19, No. 5, May 1952, pp.329-332, 340.

Downwash and sidewash angles were measured with a conical probe in vertical planes 0.5, 1.0, and 1.5 chord lengths downstream of a rectangular wing of biconvex section. Finely spaced measurements were taken to determine the downwash field in the region of steepest gradients, with the result that the rolling up of the vortex sheet was well defined. The experimental results are compared with the theoretical solutions calculated from the measured wing loading. The Mach Number and dynamic pressure in the empty tunnel and behind the wing were also determined. The free-stream Mach Number was 1.60, and the Reynolds Number, based on wing chord, was 580,000.

Davis, T.

"EXPERIMENTAL INVESTIGATION OF DOWNWASH AND SIDEWASH BEHIND A RECTANGULAR WING AT A MACH NUMBER OF 1.60"

UAC Meteor Report UAC-45, Jan. 1950, United Aircraft Corp., Hartford, CT.

Downwash and sidewash angles in planes 0.5, 1.0 and 1.5 chord lengths behind a rectangular planform wing were experimentally determined. The wing had an aspect ratio of 2.7 and a 6 per cent thick biconvex airfoil section. Measurements were made with a Reynolds number of 580000 based on the wing chord. Mach number and dynamic pressure at the test points were also determined. The experimental results agreed with the linearized theory in the plane of the wing, but deviated above and below the wing.

Davydov, A. A., Konstantinovskaya, T. V., Lutsii, A. E., Kharitonov, A. M., Shevchenko, A. M. and Shmakov, A. S.

"MODELING A SUPERSONIC FLOWFIELD IN THE CORE OF THE WINGTIP VORTEX AT MACH 6"

Mathematical Models and Computer Simulations, Vol. 5, No. 1, 2013, pp. 25-36.

In this paper numerical calculations of a wingtip vortex for various wing angles of attack are presented, and the resulting flow modes are compared with each other and with the experimental data. Numerical computations were performed at the Keldysh Institute of Applied Mathematics, making use of the Spalart-Allmaras turbulence model. Experiments were carried out at the Institute of Theoretical and Applied Mechanics, Siberian Branch (SB), Russian Academy of Sciences (RAS), Khristianovich, Russia.

Dazin, A., Dupont, P. and Stanislas, M.

"EXPERIMENTAL CHARACTERIZATION OF THE INSTABILITY OF THE VORTEX RING. PART I: LINEAR PHASE"

Experiments in Fluids, Vol. 40, 2006, pp. 383-399

The results of experiments performed to study the linear phase of the instability of vortex rings are presented. The experiments were performed in water. The vortex rings are generated by pushing water through the cylindrical nozzle of a pipe submerged in an aquarium. The experiments were made with the help of planar laser induced fluorescence as well as 2D2C and 2D3C particle image velocimetry. They show the straining field causing the instability, and for the first time experimentally the growth of a band of linear unstable modes. They also confirm previous studies concerning the shape of the instability and theories predicting the number of waves and the bandwidth of unstable modes. However, the measurement of the growth rate shows the influence of viscous damping, and consequently, the limit of the theories based on the hypothesis of an ideal fluid.

Dazin, A., Dupont, P. and Stanislas, M.

"EXPERIMENTAL STUDY OF THE NON-LINEAR PHASE OF THE VORTEX RING INSTABILITY"

12th International Symposium on Applications of Laser Techniques to Fluid Mechanics, July 2004, Lisbon, Portugal.

The first stage of the instability of a vortex ring is linear and characterized by the growth of an azimuthal stationary wave which develops around the ring. Its origin, shape, number of waves and growth rate are predicted by theoretical works. Experimental and numerical results in viscous fluids fit well with those predictions based on an ideal fluid hypothesis. On the other hand, the next stages of the development of the instability (which are non-linear) are not well known. Only few phenomena are described, in an isolated way, in various partial contributions. The aim of this paper is to report a

complete experimental investigation made on the non-linear phase of the instability of the vortex ring. The vortices were produced in water and their Reynolds number was varied from 2650 to 6100. Visualizations were performed using Planar Laser Induced Fluorescence and measurements with 2D2C and 2D3C Particle Image Velocimetry. Based on a Fourier analysis of the results, it appears that the non-linear phase begins by the development of the harmonics of the linear modes (first unstable mode). But the growth of those harmonics is rapidly stopped by the development of low order modes. Then appears a $m=0$ mode, which corresponds to a mean azimuthal velocity around the vortex. Simultaneously, secondary vortical structures develop all around the vortex in its peripheral zone. These vortical structures are linked with the ejection of vorticity in the wake of the vortex and they appear just before the transition towards turbulence. A tentative is made here to place chronologically all these phenomena to propose a scenario from the end of the linear phase to turbulence.

Dazin, A., Dupont, P. and Stanislas, M.

"EXPERIMENTAL CHARACTERIZATION OF THE INSTABILITY OF THE VORTEX RINGS. PART II: NON-LINEAR PHASE"

Experiments in Fluids, Vol. 41, 2006, pp. 401-413

The first stage of the instability of a vortex ring is linear and characterized by the growth of an azimuthal stationary wave which develops around the ring. Theoretical works predict its origin, shape, number of waves and growth rate. Apart for the growth rate, experimental and numerical results in viscous fluids fit well with the predictions based on an ideal fluid hypothesis. On the other hand, the next stages of the development of the instability (which are non-linear) are not well known. Only few phenomena are described, in an isolated way, in various partial contributions. The aim of this paper is to report on a complete experimental investigation of the non-linear phase of the instability of the vortex ring. The vortices were produced in water and their Reynolds number was varied from 2,650 to 6,100. Visualizations were performed using planar laser induced fluorescence and measurements with 2D2C and 2D3C particle image velocimetry. Based on a Fourier analysis of the results, it appears that the non-linear phase begins with the development of harmonics of the linear modes (first unstable modes). But the growth of those harmonics is rapidly stopped by the development of low order modes. Then appears an $m=0$ mode, which corresponds to a mean azimuthal velocity around the vortex. Simultaneously, secondary vortical structures develop all around the vortex in its peripheral zone. These vortical structures are linked with the ejection of vorticity in the wake of the ring and they appear just before the transition towards turbulence. A tentative is made here to place all these phenomena chronologically, in order to propose a scenario for the transition from the linear phase to turbulence.

de Bruin, A.

"A SUMMARY OF EXPLOITABLE RESULTS FOR ENHANCED SAFETY AND/OR AIRPORT CAPACITY, RESULTS FROM THE FAR-WAKE SYNTHESIS ACTIVITY"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 200.

Within the EU co-funded project FAR-Wake, fundamental aspects of airplane wake vortex formation and decay were studied. The project considered wake instability and decay, vortex interactions with jets and wakes and wake transport and decay in head and cross-wind conditions near the ground. Important advances were made in the understanding of the physical phenomena. Within the Synthesis task of the project, a thorough analysis of the results has been made to investigate the implications for real aircraft wakes with respect to wake vortex safety and airport capacity issues. The presentation will give an overview of these exploitable results including an assessment of their importance and additional research needed for their application.

de Bruin, A.

"WAKE VORTEX EVOLUTION AND ENCOUNTER (WAVENC)"

Air and Space Europe, Vol. 2, Issue 5, September-October 2000, pp. 84-87

WAVENC was a short research project to improve understanding of the evolution of aircraft wake vortices and of their impact on the safety of flight of following aircraft. The work included numerical modelling of vortex behavior, flight simulation and analysis of measured encounter data. This article describes some of the main results.

de Bruin, A. C.

"WAVENC, WAKE VORTEX EVOLUTION AND WAKE VORTEX ENCOUNTER, PUBLISHABLE SYNTHESIS REPORT"

NLR TR-2000-079, April 2000, National Aerospace Lab., Amsterdam, The Netherlands.

The main short-term goal of the WAVENC project was to address wake vortex encounter safety aspects. This is achieved by developing realistic models for the wake vortex evolution and for computing the aerodynamic forces and moments on an aircraft flying through a given wake vortex disturbance flow field. These models are implemented in realistic flight simulation environments for studying wake vortex encounter at the glide path during final approach, either with auto-land control or with pilot control. The project includes theoretical, experimental, and computational work by eight partners. The main technical objectives of the WAVENC project have been achieved. The present report gives a summary of the main outcomes of the project. The results will be exploited and further extended in the new EU funded projects S-Wake and C-Wake.

de Bruin, A. C.

"PROSPECTS FOR HEAD- AND CROSSWIND DEPENDENT AIRCRAFT SEPARATIONS IN THE CONTEXT OF WAKE VORTEX SAFETY AND AIRPORT CAPACITY, APPLICATION TO SCHIPHOL AIRPORT"

ICAS 2006, September 2006, Hamburg, Germany.

The current wake vortex separation rules are generally believed to be sufficiently safe, but rather conservative in certain weather conditions. The present report addresses the possibility of applying head- and/or crosswind depending reduced aircraft separations during the landing and departure phase. Taking the mean annual wind conditions for aircraft operations at Schiphol Airport as an example, an initial estimate is made of the potential landing and departure capacity benefits for different wind-dependent aircraft separation strategies. For steep approach procedures (as being considered for reduced noise emissions) the initial assessments indicate a large potential gain in airport capacity. However, further study will be needed to assess the practical limitations and safety aspects for the proposed modified aircraft separation strategies.

de Bruin, A. C.

"PROSPECTS FOR HEAD- AND CROSSWIND DEPENDENT AIRCRAFT SEPARATIONS IN THE CONTEXT OF WAKE VORTEX SAFETY AND AIRPORT CAPACITY"

Report NLR-TP-2005-398, June 2006, National Aerospace Laboratory, Eindhoven, The Netherlands.

The current wake vortex separation rules are generally believed to be sufficiently safe, but rather conservative in certain weather conditions. The present report addresses the possibility of applying head- and/or crosswind depending reduced aircraft separations during the landing and departure phase. Taking the mean annual wind conditions for aircraft operations at Schiphol Airport as an example, an initial estimate is made of the potential landing and departure capacity benefits for different wind-dependent aircraft separation strategies. For steep approach procedures (as being considered for reduced noise emissions) the initial assessments indicate a large potential gain in airport capacity. However, further study will be needed to assess the practical limitations and safety aspects for the proposed modified aircraft separation strategies.

de Bruin, A. C.

"ESTIMATION OF EXHAUST VELOCITIES AND TEMPERATURES FOR VARIOUS OPERATION PHASES OF A MODERN HIGH BY-PASS TURBOFAN"

NLR-CR-2005-641, Nov. 2005, National Aerospace Laboratory, Amsterdam, The Netherlands

Within the FAR-Wake project fundamental research is focused on the the precise role of vortex instabilities on aircraft wing wake decay (WPI), the effects of engine jets and fuselage wakes (WP2), and the influence of ground proximity on wake evolution, relevant to the airport environment (WP3). Experimental and numerical investigations as well as theoretical/analytical studies are made and, where appropriate, this is complemented with existing knowledge and data from previous projects. The activities conducted as described in the present report, will support the Work Package WP2, where the effect of jets interacting with wake vortices will be investigated.

de Bruin, A. C. and Ganzevles, F. L. A.

"EXPERIMENTAL STUDY OF VORTEX MERGING IN THE WAKE OF A PART SPAN FLAP MODEL"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

As part of the European funded project Wake Vortex Characterization and Control (C-Wake), extensive wake surveys were made up to 30 wingspans behind a model with a simple straight wing and a wingspan of 0.6 m. Different model configurations (a full span flap configuration without- and a part-span flap configuration with and without spoiler elements) were tested near a lift coefficient of $CL=1.6$. The wake was measured in detail from the near wake up to the extended near wake (between 0.45 and 30 wingspans downstream of the wing). Two different measurement techniques are employed: a rake with five-hole probes and PIV techniques (both a standard and three component PIV (3C-PIV)). The experimental data allow a direct comparison between results at several downstream planes.

de Bruin, A. C. and Schrauf, G.

"WAKE VORTEX RESULTS FROM THE AWIATOR PROJECT"

Report NLR-TP-2007-527, December 2007, National Aerospace Laboratory, Marknesse, The Netherlands.

Within the wake vortex task of the AWIATOR project (2002-2007) wake alleviation concepts were tested in wind tunnels, water towing tanks and ONERA B-20 catapult facility. In addition, advanced numerical methods were applied. The aim of this work was to down-select promising configurations to be tested in flight on an A340 aircraft in landing configuration. NLR managed the wake vortex task of AWIATOR and participated in the technical work by prescribing a mandatory wake characterization methodology to be used by all partners, by measuring atmospheric turbulence conditions and performing flow visualizations during the flight tests and by performing safety assessment studies with the WAVIR methodology for the baseline and modified A340 wing configurations tested. The present report gives a summary of the total work performed in the wake vortex task of the AWIATOR project (2002-2007).

de Bruin, A. C. and Schrauf, G.

"WAKE VORTEX RESULTS FROM THE AWIATOR PROJECT"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-008, September 2007, pp. 1027-1035

Wake turbulence poses a potential hazard to following aircraft. Therefore, minimum aircraft separation distances, based on an aircraft weight classification scheme, are recommended by ICAO in order to assure proper safety during all flight phases. These pose a limiting factor for the capacity at congested airports. If modifications of the wing configuration can be shown to alleviate the strength and fasten the decay of the wake vortices, this potentially allows a mitigation of aircraft separation rules. The EU co-funded projects EURO-WAKE, C-Wake and the wake vortex task of AWIATOR form a

continuous line of research focused on the effects of wing modification on wake roll-up and decay. The EUROWAKE project (1996-1998) concentrated on wake formation and roll-up in the near wake. The C-Wake project (2000-2003) investigated wing span-loading concepts and other wing modifications up to the extended wake region using wind tunnel, towing tank, B10 catapult facility and a limited number of flight tests with the A340-300 in landing configuration, using ground-based LIDAR. The AWIATOR project (2002-2007) focused on the selection of wake alleviation concepts, to be tested in flight on the same aircraft, also in landing configuration. A down-selection of promising configurations was made from extensive CFD simulations, wind tunnel experiments, free-flying model tests and tests in a large towing tank facility. This paper gives an overview of the methods used for the selection process, the physical mechanisms exploited and the wake alleviation results obtained.

de Bruin, A. C., Hegen, S. H., Rohne, P. B. and Spalart, P. R.

"FLOW FIELD SURVEY IN TRAILING VORTEX SYSTEM BEHIND A CIVIL AIRCRAFT MODEL AT HIGH LIFT"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 25-1 to 25-12

The roll-up of the trailing vortex system behind a generic civil aircraft wind tunnel model with extended flaps and slats is studied up to 5 wing spans downstream. A laser light sheet flow visualization technique is used and detailed flow field measurements are made with a spanwise traversable rake with five-hole probes. The measurement results are compared against calculations with the 2D vorticity transport equation.

de Bruin, A. C., Speijker, L. J. P., Moet, H., Krag, B. and Mason, S.

"S-WAKE: ASSESSMENT OF WAKE VORTEX SAFETY"

NLR-TP-2003-243, May 2003, National Aerospace Laboratory, Amsterdam, The Netherlands

This report summarizes the work and outcomes of the multi-disciplinary European research project S-Wake. Fourteen partners collaborated in the project. The aim of the project was to develop and apply tools for the assessment of wake vortex safety. The work consisted of five inter-related Work Packages: Wake vortex behavior in the atmosphere; Aerodynamic models for wake vortex encounter (including wake encounter flight tests); Flight simulations; Probabilistic safety assessment; and Safety assessment from flight data recording data collection.

de Bruin, A. C., van Baren, G. and Speijker, L.

"AN ASSESSMENT OF WAKE VORTEX SAFETY ASPECTS WITH A PROBABILISTIC APPROACH, AS PART OF THE S-WAKE PROJECT"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 200.

The potential risk imposed by wake vortices can be an important constraining factor for airport capacity. To investigate the levels of flight safety under current ATM rules and guide possible new ATM procedures that may have improved safety and/or increased capacity, a European co-funded research project S-Wake has started. The S-Wake project aims to develop and apply tools for assessing appropriate (safe) wake vortex separation distances. The specific objectives of S-Wake are: to define suitable weather categories for wake vortex safety for aircraft on the approach glide path; to improve the physical understanding of wake vortex evolution and decay in the atmosphere; to establish realistic flight simulation environments for investigating wake vortex encounter safety aspects and pilot's response; to establish a validated probabilistic safety assessment method; to analyze the safety aspects for current practice by collecting and analyzing large amounts of flight data recordings and to define possible new concepts which allow a safe mitigation of current separation rules under certain conditions. A probabilistic approach is followed to evaluate wake vortex induced risk related to different separation distances between landing aircraft on a single runway.

De Gregorio, F. and Ragni, A.

"WAKE VORTEX CHARACTERISATION IN TOWING TANK FACILITIES USING PIV TECHNIQUE"

AIAA Paper No. 2003-0093, Reno, NV, January 2003

This paper summarizes two different experimental campaigns aimed to the wake vortex characterization. The experiments were performed, first at HSVA (Hamburg) small towing tank and after a period of six months at INSEAN (Rome) large towing tank using Particle Image Velocimetry (PIV) technique to detect the wake evolution and decay from the near field up to the mid/far field. A 1/48 scaled four engines commercial aircraft model was used, the model allowed to investigate different configurations simulating both cruise and landing configuration. For the last configurations different slat and flap deflection angles were tested, furthermore the influence of the under carriage as well as the influence of horizontal tail plane on the wake vortex behavior was investigated varying velocity and angle of attack. Different towing tank sizes were used for investigating the wall effect influence and the capability to reach the mid/far field condition. The adopted experimental set-ups, the velocity fields measured, the main magnitudes characterizing the vortex phenomenon, the wake vortex motion and persistence are presented.

de Haan, S.

"MEASURING ATMOSPHERIC STABILITY WITH GPS"

Journal of Applied Meteorology and Climatology, Vol. 45, March 2006, pp. 467-475.

Nowcasting of convective systems plays a crucial role in weather forecasting. The strength of convection depends on the (in)stability of the air column. The stability can be detected by radiosonde observations. However, these observations are not frequent (typically 2 times per day) and are expensive to deploy. In this article a method is presented to detect the stability of the atmosphere based on high-frequency global positioning system (GPS) path-delay observations. The convection

parameter derived from these observations is the power of the non-isotropic GPS path-delay signal. Comparisons with the convective available potential energy obtained from radiosonde observations show a correlation with the convective parameter obtained from GPS. This result implies that, because of the continuous availability of GPS estimates and the good land coverage, this method of detecting atmospheric stability may be beneficial to forecasters.

de Haan, S., Bailey, L. J. and Konnen, J. E.

"QUALITY ASSESSMENT OF AUTOMATIC DEPENDENT SURVEILLANCE CONTRACT (ADS-C) WIND AND TEMPERATURE OBSERVATION FROM COMMERCIAL AIRCRAFT"

Atmospheric Measurement Techniques, Vol. 6, 2013, pp. 199-206.

Aircraft observations of wind and temperature are very important for upper air meteorology. In this article, the quality of the meteorological information of an Automatic Dependent Surveillance-Contract (ADS-C) message is assessed. The ADS-C messages broadcast by the aircraft are received at air traffic control centers for surveillance and airline control centers for general aircraft and dispatch management. A comparison is performed against a global numerical prediction (NWP) model and a wind and temperature observations derived from Enhanced Surveillance (EHS) air-traffic control radar which interrogates all aircraft in selective mode (Mode-S EHS). Almost 16000 ADS-C reports with meteorological information were compiled from the Royal Dutch Airlines (KLM) database. The length of the data set is 76 consecutive days and started on 1 January 2011. The wind and temperature observations are of good quality when compared to the global NWP forecast fields from the European Centre for Medium-Range Weather Forecasts (ECMWF). Comparison of ADS-C wind and temperature observations against Mode-S EHS derived observations in the vicinity of Amsterdam Airport Schiphol shows that the wind observations are of similar quality and the temperature observations of ADS-C are of better quality than those from Mode-S EHS. However, the current ADS-C data set has a lower vertical resolution than Mode-S EHS. High vertical resolution can be achieved by requesting more ADS-C when aircraft are ascending or descending, but could result in increased data communication costs.

de Jong, P. M. A., van der Laan, J. J., i 't Veld, A. C., van Paassen, M. M. and Mulder, M.

"WIND-PROFILE ESTIMATION USING AIRBORNE SENSORS"

Journal of Aircraft, Vol. 51, No. 6, November-December 2014, pp. 1852-1863.

Wind is one of the major contributors to uncertainties while flying continuous-descent operations. When aircraft are issued a required time of arrival over the runway threshold, as is foreseen in some of the future air-traffic-system concepts, the onboard availability of both dependable and accurate wind estimates becomes a necessity for spacing. This paper presents a method for real-time estimation of a wind profile in the terminal maneuvering area, based on data transmitted by nearby aircraft. The algorithm produces high-resolution and real-time wind-profile estimates, usable for accurate trajectory prediction to improve continuous-descent operations and spacing performance. The wind estimation algorithm is tested with mode-S derived meteorological data from Amsterdam Airport Schiphol. It

combines multiple measurements from different aircraft to estimate the current wind profile using a Kalman filter. Using these wind-observation data, the algorithm showed an rms in the estimation error of 1.35 kt, which is lower than the observed rms measurement error of 1.94 kt, reducing the uncertainty when used in trajectory prediction. Another simulation study investigating aircraft spacing showed a clear benefit of using wind estimates along the own trajectory by reducing the spacing time error and improving control space.

de Jong, R. C. and Mulder, J. A.

"ACCURATE ESTIMATION OF AIRCRAFT INERTIA CHARACTERISTICS FROM A SINGLE SUSPENSION EXPERIMENT"

Journal of Aircraft, Vol. 24, No. 6, June-July 1987, pp. 362-370.

A novel method for the experimental determination of the aircraft center of gravity and the moments and products of inertia is presented and evaluated. The method is based on the application of statistical parameter estimation techniques to the analysis of multi-degree-of-freedom oscillations using a high-accuracy instrumentation system. An existing suspension rig, in which the aircraft can simultaneously rotate about the F and Z axes (pitch and yaw axes) and translate along the X (roll) and Y axes, is used to demonstrate the validity of the method. The inertia moments I_y and I_z , the inertia product I_{yz} , and the three coordinates of the center of gravity are simultaneously estimated from measurements of only one oscillation. The experiment is much less time-consuming compared to earlier methods, since no separate center-of-gravity measurements nor rig reconfigurations are needed. It is suggested that the remaining inertia characteristics (I_x , I_{xz} , and I_{xy}) can be simultaneously estimated after a slight modification in the suspension construction.

de Laat, T. W. G. and Coene, R.

"UNSTEADY FORCE ON SLENDER AIRCRAFT WITH FREE VORTICES IN INVISCID FLOW"

AIAA Journal, Vol. 40, No. 4, April 2002, pp. 610-618

Expressions are derived for the force on circular and wing-body contours induced by a vortex pair in a two-dimensional uniform unsteady inviscid flow, such as arise in the slender-body approximation of an aircraft. Zero-force curves for the classical vortex pair behind a circular cylinder in oncoming flow are found, and it is shown that the direction of the force can be upwind as well as downwind. A convenient expression for the force on a contour in a symmetric flow-field is obtained by conformal mapping, involving only the first- and second-order derivatives of the required transformation function. A result of practical interest for free vortices intended to enhance the lift force of an aircraft is that the force on the crossflow contour induced by vortices with a certain strength generally decreases when enlarging the width of the contour perpendicular to the direction of that force. So span reduction increases the lift generated by vortices above the wings. The position of the vortices in relation to the contour is critical, however, as there are areas that are shown, where the lift caused by the vortices is negative. The force caused by the symmetric vortex pair on the symmetric contour is independent of the speed

of the oncoming flow; the pressure distribution on the contour, however, does vary with changing speed of the oncoming flow.

de Leege, A. M. P., van Paassen, M. M. and Mulder, M.

"USING AUTOMATIC DEPENDENT SURVEILLANCE-BROADCAST FOR METEOROLOGICAL MONITORING"

Journal of Aircraft, Vol. 50, No. 1, January-February 2013, pp. 249-261.

The use of automatic surveillance-broadcast for meteorological monitoring is explored. Although originally developed for surveillance, the data that the system provides can be used to estimate wind, pressure, and temperature profiles. Two methods to estimate wind are presented. These make use of velocity vector information from a single aircraft or multiple aircraft, respectively. Air pressure is derived from the barometric altitude and height above the World Geodetic System 1984 ellipsoid. From this pressure estimate the temperature is estimated, using the hydrostatic equilibrium and the ideal gas law. To validate the methods, automatic dependent surveillance-broadcast data were collected over a 100-day period and the resulting estimates compared to Global Forecast System forecasts. Estimating wind using information from one aircraft resulted in a low number of estimates. When using data from multiple aircraft, more accurate wind estimates could be produced, at fixed time intervals and at altitude intervals. The mean absolute errors for wind speed and direction estimates were 9.2 kt and 29.0 deg, respectively. The mean errors for pressure and temperature estimates were -0.1 hPa and 0.8 K, respectively. The mean absolute errors for the pressure and temperature estimates were 0.8 hPa and 2.0 K, respectively.

de Mattos, B. S., de Paula, A. A. and Komatsu, P. J.

"CONSIDERATIONS ABOUT WINGTIP DEVICES DESIGN OF TRANSPORT AIRPLANE"

AIAA Paper 2015-3437, June 2015, Dallas, TX.

From the start of aviation, designers have been searching for methods and technologies to reduce the required fuel burn of commercial aircraft. Wingtip devices in special winglets offer a way of significant drag reduction for transport airplanes. Winglets alongside with tip tanks, raked wingtips as well as fans belong to this class of wingtip devices. Although winglets are targeted to induced drag reduction, their effects can also be extended to wave and zero-lift drag. Induced drag alone is responsible for 30-40 percent of the overall drag of a transport airplane at long-range cruise condition and for considerably downgrading the climb performance of fixed-wing aircraft. Better investigation in this field employing CFD tools and extensive wind-tunnel testing has allowed the rise of efficient winglet designs in recent times. Several of newly designed aircraft configurations embody winglets and many of the older ones are being retrofitted. However, there are discussions concerning the best cost/benefit ratio of reducing induced drag of a transport plane with wingtip devices. Another big issue is the associated penalties to the configuration caused by winglets when compared to a simple wingtip extension. Two winglet optimization studies were carried-out for a 70-seat airliner. In the first simulation, wing and winglet were optimized for cruise and field performance. In the second study, optimization was carried out for

wings without winglet. The Pareto front for the configuration with winglets lies above the one obtained from the optimization for wing-body alone, justifying the adoption of winglets from the aerodynamic point of view.

de Mattos, B. S., Macedo, A. P. and da Silva Filho, D. H.

"CONSIDERATIONS ABOUT WINGLET DESIGN"

AIAA Paper 2003-3502, June 2003, Orlando, FL.

From the beginning of aviation designers are searching for methods and technologies for reducing the required fuel burn of commercial aircraft. Wingtip devices aim the reduction of induced drag, which is responsible for 30-40% of the total drag of a transport-aircraft at long-range cruise condition and for considerably downgrading the climb performance of an aircraft. Winglet alongside with tip tanks, raked wingtips, aligned fans belong to this class of devices. Better investigation in this field employing CFD tools and extensive wind-tunnel testing has allowed the rising of efficient winglet designs in recent times. Several of newly designed aircraft configurations embody winglets and many older ones are being retrofitted. However, there are discussions concerning the best cost/benefit of reducing induced drag of a transport plane with wingtip devices. Another big issue is the associated penalties to the configuration caused by winglets when compared to a simple wingtip extension. This paper addresses some of these issues based on the expertise obtained designing winglets for several aircraft configurations, ranging from a business jet and a twinjet airliner for 70 passengers to an AEW&C military airplane.

de Saint Victor, X.

"THE ACTIVITIES OF THE ONERA PROJECT-- WAKE VORTEX DYNAMICS"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

The ONERA federated research project 'Wake Vortex Dynamics' was established in 1997. The following tasks were defined: Understanding of the phenomenon of wake vortices by the means of the analysis of the near and far field, the study of the development of the turbulence, the study of the instabilities, the analysis of the different means to use to destruct the wake. Modelling by means of DNS and LES or RANS calculations to simulate the evolution of the wake, the merging, the ground-effect or the jet/wake vortex interaction. The problem of the wake vortex encounter is also tackled using a flight mechanics code. Development of new measurement techniques as PIV or LIDAR using various facilities as the free flight facility or the water tunnel THALES.

De Souza, F. and Faghani, D.

"STUDY OF NEAR-FIELD WING-TIP VORTICES USING PARTICLE IMAGE VELOCIMETRY AND HOT-WIRE ANEMOMETRY"

Proceedings of 9th International Symposium on Flow Visualization, Edinburgh, Scotland, August 2000, pp. 399-1-399-11

The near-field development of tip vortices generated by rectangular planform wings with symmetrical profiles and different end-cap geometries is investigated using both Particle Image Velocimetry (PIV) and hot-wire anemometry. PIV Measurements are obtained in several cross-flow planes at up to five chord lengths downstream of the trailing edge. These are complemented by hot-wire anemometry measurements using a four-sensor probe. Comparison between these two independent measurement techniques allows some observations to be made on their accuracy in the highly sensitive flow region in and around the vortex core. The study also provides some insight on the effects of the wing end-cap shape and angle of incidence on the near-field flow structure.

de Souza, F. and Lee, B. H. K.

"MEAN FLOW AND TURBULENCE MEASUREMENTS IN THE NEAR FIELD OF A FIGHTER AIRCRAFT WING-TIP VORTEX AT HIGH REYNOLDS NUMBER AND TRANSONIC FLOW CONDITIONS"

ESAIM: Proceedings, Vol. 7, 1999, pp. 120-129

Mean and turbulent flow characteristics of the wing-tip vortex generated by a 6% scale model of the F/A-18 fighter aircraft equipped with AIM-9 sidewinders were investigated experimentally. This particular configuration was studied as part of the NRC/IAR stores clearance and certification program. However, the present study focuses on the near field structure of the tip vortex, as the existing literature contains relatively little information on tip vortices generated at such high Reynolds numbers (4,400,000, based on wing chord), and even less on the tip vortices of fighter aircraft. The experiments were conducted in the transonic test section of the NRC/IAR 1.5m x 1.5m tri-sonic blowdown wind tunnel. The present paper documents results obtained in a single cross-flow plane located immediately downstream of the wing trailing edge, for two angles of attack, 4.5 degrees and 13 degrees, and at a single freestream Mach number of 0.75. Mean velocities and flow angularities were measured using a five-hole directional velocity probe as well as an x-array constant temperature hot-wire probe. The latter also provided estimates of the turbulence intensities, Reynolds stresses and turbulent kinetic energy in the measurement plane. The results shed some light on the fairly complex interaction, particularly at the higher angle of attack, of the wing-tip vortex and the wake of the AIM-9 tip missile.

de Souza, J. M. and Catalano, F. M.

"MULTI-DISCIPLINARY DESIGN OPTIMIZATION OF A BLENDED WINGLET"

31st Congress of the International Council of the Aeronautical Sciences (ICAS 2018), September 2018, Belo Horizonte, Brazil.

To reduce operating costs directly related to fuel burn, it is proposed the development of a blended winglet optimized for a commuter aircraft of 11 passengers. Initially a brief description of the problem is made, as well as the background of the wingtip devices evolution. The optimization method used to model the physical phenomena in question, the drag generated by lift was a Vortex Lattice Method

(VLM) code based on the Trefftz-Plane theory for counting induced drag. After the iterative process the results are analyzed, presenting the comparisons between the aircraft without / with the final winglet. These comparisons cover several areas of aeronautics, such as aerodynamics, loads and performance.

De Visscher, I., Bricteux, L. and Winckelmans, G.

"AIRCRAFT VORTICES IN STABLY STRATIFIED AND WEAKLY TURBULENT ATMOSPHERES: SIMULATION AND MODELING"

AIAA Journal, Vol. 51, No. 3, March 2013, pp. 551-566.

This study investigates the influence, on aircraft wake vortex behavior, of atmospheres that are stably stratified (neutral to very strong) and weakly turbulent, by means of large-eddy simulations at very high Reynolds number and on relatively fine grids. The atmospheric fields are first generated using large-eddy simulations of forced and stratified turbulence reaching a statistically stationary state. The obtained fields are shown to be realistic and consistent with the literature. A pair of counter-rotating vortices, with relatively tight cores, is then put in the obtained fields and evolved. The evolution of the wake vortex topology, transport, and decay is analyzed in depth by measuring the wake vortex characteristics in all cross planes. The vortex transport and deformation are related to the stratification and turbulence levels. Stratification combined with weak turbulence is seen to strongly affect the Crow instability development. Different decay mechanisms are identified, related to the interactions with the turbulence, the turbulent baroclinic vorticity, and/or between the vortices themselves. Finally, improved simplified models of vortex altitude evolution and of vortex decay (with two phases) are proposed and calibrated on the present results. They yield good agreement with the large-eddy simulation results and are usefully integrated in our operational models.

De Visscher, I., Bricteux, L. and Winckelmans, G.

"LES OF AIRCRAFT WAKE VORTICES EVOLVING IN A STABLY STRATIFIED AND WEAKLY TURBULENT ATMOSPHERE"

Fifth European Conference on Computational Fluid Dynamics, June 2010, Lisbon, Portugal.

The aim of this study is to investigate the influence of weakly turbulent stable stratification of the atmosphere on aircraft wake vortex behavior, by means of Large Eddy Simulations (LES). To best represent the atmospheric conditions, the stratified and weakly turbulent fields are here first generated, using LES of forced and stratified turbulence. The obtained fields are non-isotropic. LES of a pair of counter-rotating vortices, with relatively tight cores, evolving in the obtained fields are then performed. Different stratification levels are investigated, from low to very high, and all with weak turbulence. The simulations are performed at very high Reynolds number; much higher than in previous work, thus more realistic. The current investigation is performed using a pseudo-spectral code with various sub-grid scale models. The influence of the domain size is also investigated, with box sizes also allowing the Crow instability development. The chosen resolution ensures that the essential dynamics of the vortices is properly captured. The time evolution of the wake vortex characteristics

(positions and circulation) is studied as a function of the stratification level. They are also compared to those obtained from previous simulations performed with stratification but without turbulence. It also appears that the turbulence of the temperature field has a strong impact on the decay of the vortices. It enhances the development of 3-D instabilities in the baroclinic vorticity. Hence, this quickens its interaction with the primary vortices, leading to a fast decay. A simplified model of altitude evolution is also proposed and fitted on the present results. Such model can be used in operational models for predicting the wake vortex behavior (transport and decay).

De Visscher, I., Bricteux, L., Karamelas, S., Winckelmans, G., Holzaepfel, F., Baumann, R., Roblin, Y. and Schroder, K.

"EDDF-2 DATABASE ANALYSIS AND PERFORMANCE ASSESSMENT OF THE WAKE VORTEX MODELS ON THE EDDF-1 AND EDDF-2 DATABASES"

CREDOS Report D2-5, June 2009, Universite catholique de Louvain, Louvain-la-Neuve, Belgium.

This deliverable includes the contributions of UCL, DLR and Airbus-D concerning the use of the two measurement campaign databases, EDDF-1 and EDDF-2. The deliverable includes a detailed analysis of the EDDF-2 database, and a performance assessment of the operational prediction models (DVM/PVM of UCL and D2P/P2P of DLR) as compared to the data of the two campaigns. The results of a benchmark of the two deterministic models (DVM and D2P) performed by Airbus using some selected cases of the EDDF-1 database, are also reported.

De Visscher, I., Lonfils, T. and Winckelmans, G.

"FAST-TIME MODELING OF GROUND EFFECTS ON WAKE VORTEX TRANSPORT AND DECAY"

Journal of Aircraft, Vol. 50, No. 5, September-October 2013, pp. 1514-1525.

A fast-time model for wake vortex behavior prediction in ground proximity is presented. This model considers the combined effects of ground proximity and wind (both crosswind and headwind components) on the wake vortex transport and decay. It aims to mimic the whole flow using a limited set of vortex particles to model both the primary two-vortex system and the ground-generated secondary vorticity. A redistribution of the vortex particles is also included in the model to limit the number of used particles and hence, guarantee a high computational efficiency. The model is integrated in the deterministic wake vortex model, which is a software that predicts, also in real-time, the temporal evolution of the wake vortices generated by a given aircraft evolving in given ambient meteorological conditions. The new ground effect model capacity is assessed using data from a measurement campaign and from large-eddy simulations. It is found that the model can reproduce the wake vortex behavior (both for transport and decay) for the most relevant times required for air traffic management applications.

De Visscher, I., Lonfils, T. and Winckelmans, G.

"IMPROVEMENT OF THE DETERMINISTIC/PROBABILISTIC WAKE VORTEX MODEL (DVM/PVM) FOR THE COMBINED EFFECTS OF GROUND AND METEOROLOGY"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

UCL has developed a real-time tool to predict the wake vortex transport and decay: the Deterministic/Probabilistic wake vortex model (DVM/PVM). The DVM, based on the Method of Discrete Vortices integrates, in time, various physical models to forecast in real-time the transport and decay of the wake vortices in one computational gate (i.e., one slice in space along the flight path) generated by a given aircraft in given meteorological conditions. It includes models of the two-phase decay, the Near-/In-ground Effects (NGE/IGE), the wind shear and the stratification effects. Because probabilistic modelling and assessment of wake vortices is what is operationally required, an upper software layer was also developed. For each probabilistic run, several deterministic runs are computed, with variations on the impact parameters (i.e., met. conditions, aircraft characteristics and related physical model coefficients). A statistical analysis (e.g., PDF, mean, variance, confidence interval) is then performed on the deterministic result samples. The IGE model employs secondary vortex particles close to the ground modelling the separation of the wall boundary layer induced by the primary wake vortices in the proximity of the ground. These secondary vortices interact with the primary ones and induce rebound as well as the highly enhanced decay of the primary vortices after rebound, using a new 'Particle Strength Exchange' approach.

De Visscher, I., Winckelmans, G. and Treve, V.

"A SIMPLE WAKE VORTEX ENCOUNTER SEVERITY METRIC"

Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015), June 2015, Lisbon, Portugal.

This paper presents a severity metric supporting the characterization of the effect of a wake vortex encounter on a follower aircraft. The proposed metric is the Rolling Moment Coefficient computed using various simplified assumptions that lead to a simple and usable metric. The metric can indeed be computed using available aircraft data. The paper also presents the assessment of the metric based on the results of a wake vortex encounter flight test performed by Airbus. The use of the proposed metric yields good agreement with the experimental data. Because it is simple, yet realistic compared to experimental data, the metric can be used in a relative safety analysis permitting a reduction of the wake turbulence separations compared to today's ICAO standard, as was done in the framework of the RECAT-EU project.

De Visscher, I., Winckelmans, G. and Treve, V.

"CHARACTERIZATION OF AIRCRAFT WAKE VORTEX CIRCULATION DECAY IN REASONABLE WORST CASE CONDITIONS"

AIAA Paper 2016-1603, January 2016, San Diego, CA.

This paper presents a methodology allowing the characterization of aircraft wake vortex circulation decay in reasonable worst-case conditions. These reasonable worst-case conditions correspond to wake vortices evolving in ground proximity and in meteorological conditions that are unfavorable in terms of wake circulation decay. The decay characterization is based on the analysis of a large measurement database. From the data analysis, it is observed that the dimensionless decay curves of wake vortices generated by various Heavy aircraft types collapse on a single generic curve. This generic dimensionless decay curve is used to support the characterization of the wake vortex encounter severity on a follower aircraft. The proposed generic decay curve can indeed be used, when combined with initial vortex circulation and spacing, in a relative safety analysis permitting a reduction of the wake turbulence separations compared to today's ICAO standard, as was done in the framework of the RECAT-EU project.

De Visscher, I., Winckelmans, G., Desenfans, O. and Lonfils, T.

"OVERVIEW OF UCL OPERATIONAL TOOLS FOR PREDICTING AIRCRAFT WAKE VORTEX TRANSPORT AND DECAY: THE DETERMINISTIC/PROBABILISTIC WAKE VORTEX MODELS (DVM/PVM) AND THE WAKE4D PLATFORM"

Report, July 2008, Universite catholique de Louvain, Louvain-la-Neuve, Belgium.

The three UCL operational tools: (1) The '3-D space + time' (thus 4-D) wake vortex prediction platform software, WAKE4D, handles the space and time discretization of the aircraft trajectory. It creates n computational gates (n 'slices of space along the flight path'); (2) In each of these gates, one probabilistic forecast of the wake vortex behavior is performed using the Probabilistic wake Vortex Model (PVM); and (3) The PVM performs N deterministic predictions with variations on the impact parameters, using the Deterministic wake Vortex Model (DVM) as a sub-tool, in a Monte-Carlo approach. The DVM thus forms the core of the entire tool. UCL has implemented, within this software, several physical models that forecast the wake vortex behavior. These models have been developed, calibrated, and assessed, for more than ten years. The WAKE4D, and its subcomponents PVM and DVM, constitutes a fairly mature and operational wake vortex predictor. It can simulate realistically complex wake vortex behaviors depending on atmospheric conditions and ground proximity conditions. Its real time capabilities also make it a usable wake vortex predictor for practical applications.

De Visscher, I., Winckelmans, G., Lonfils, T., Bricteux, L., Duponcheel, M. and Bourgeois, N.

"THE WAKE4D SIMULATION PLATFORM FOR PREDICTING AIRCRAFT WAKE VORTEX TRANSPORT AND DECAY: DESCRIPTION AND EXAMPLES OF APPLICATION"

AIAA Paper No. 2010-7994, Toronto, Canada, August 2010.

The WAKE4D is a '3-D space + time' wake vortex (WV) prediction platform software developed at UCL. It allows to handle complete flight scenarios in 3-D space, and with given met conditions. It simulates the transport and decay of the WV generated by an aircraft evolving along a given flight path and under those met conditions. It uses many 'computational gates' to discretize the flight path, and, in each gate,

it uses either the Deterministic wake Vortex Model (DVM) or the Probabilistic wake Vortex Model (PVM), depending on application. The DVM constitutes the core of the WAKE4D. The models used in the DVM are here briefly presented together with their assessment and use in the past. The PVM is also presented. It enables a statistical analysis of the WV behavior using the DVM as a sub-tool in a Monte-Carlo approach. The WAKE4D platform software (or any of its subcomponent model software, DVM and PVM) can be used for off-line studies or can be part of real-time operational systems. Some examples of use of the WAKE4D are presented: simulation of a detailed approach to Marseille airport with 3-D WV reconstruction, simulation in support to a time-based separation concept on approach to a generic airport, simulation of take-off with potential WV encounter analysis on a parallel arrival runway, 3-D velocity field evaluation using the WAKE4D results: case of a take-off, thus with phases of WV in ground effect, and case of a flight at high altitude taking into account the Crow instability development.

DeCroix, D., Lin, Y.-L., Arya, S. P., Kao, C.-T. and Shen, S.

"TOWARD UNDERSTANDING WAKE VORTICES AND ATMOSPHERIC TURBULENCE INTERACTIONS USING LARGE-EDDY SIMULATION"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 109-130

As aircraft wake vortices descend, they are transported by the air mass in which they are embedded and are decayed by both internal and external processes. Near the airport, these external influences are usually due to planetary boundary layer (PBL) turbulence. Using large-eddy simulation (LES), one may simulate a variety of PBL conditions. In the LES method, turbulence is generated in the PBL as a response to surface heat flux, horizontal pressure gradient, wind shear, and/or stratification, and may produce convective or unstably stratified, neutral, or stably stratified PBL's. Each of these PBL types can occur during a typical diurnal cycle of the PBL. Thus, it is important to be able to characterize these conditions with the LES method. Once this turbulent environment has been generated, a vortex pair will be introduced and the interactions are observed. The objective is to be able to quantify the PBL turbulence vortex interaction and be able to draw some conclusions of vortex behavior from the various scale interactions.

Dedesh, V. T., Zamyatin, A. N., Grigoryev, M. A., Zuev, S. A. and Zhelannikov, A. I.

"RESEARCHES OF INTERACTION OF AIRCRAFT WAKE VORTICES AND CONDENSATION TRAILS"

AIAA Paper 2013-2554, June 2013, San Diego, CA.

The report presented is devoted to aircraft wake vortices and condensation trails interaction. Condensation trails could affect heat exchanging processes in the atmosphere and deteriorate ecology by contribution to 'greenhouse effect.' With the aim of investigation of condensation trails formation and minimization of its negative effect on ecology there was developed in the PJSC 'Flight Research Institute named after M. M. Gromov' a complex methodology of quantitative assessment of condensation trails characteristics and its formation prognosis during cruise flights of aircraft with jet

engines of various types. During flight tests it was demonstrated the necessity of accounting of aircraft condensation trails and wake vortices interaction and it is implemented in the methodology. Mathematical model of condensation trails and wake vortices development and interaction was created for that purpose. Using the model developed there were performed the calculations of different aircraft condensation trails and wake vortices and there were carried out the researches of the influence of atmospheric conditions, presence of axial flows in the vortices nuclei and engines location on the wing on the process of condensation trail and wake vortex interaction. The description of this mathematical model and some research results are presented.

Dee, F. W. and Nicholas, O. P.

"FLIGHT MEASUREMENTS OF WING-TIP VORTEX MOTION NEAR THE GROUND"

ARC Paper CP-1065, January 1968, Royal Aircraft Establishment, Bedford, England.

Tests have been made to measure the movement of the wing tip vortices from a Hunter aircraft flying at 170 knots approximately 35 feet above a runway, in a variety of wind conditions. Measurements were limited to a maximum time of 20 seconds after vortex generation. During this period the theoretical predictions presented are in good general agreement with the observed motions; however significant differences did occur. There was no clear indication as to whether the vortices decayed more rapidly in the presence of the ground and atmospheric turbulence, than would have been expected from the ground in calm air. Limited tests were also made to study the vortex mutual interaction away from the ground.

Deierling, W. and Williams, J. K.

"RELATIONSHIPS BETWEEN LIGHTNING AND CONVECTIVE TURBULENCE"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 8, 2016, Springer International Publishing Switzerland, pp. 179-192.

Total lightning has been shown to correlate well with thunderstorm dynamics. Thus, correlations may exist between in-cloud convective turbulence and total lightning activity. Over the continental United States, the NEXRAD Turbulence Detection Algorithm (NTDA) provides three-dimensional (3D) fields of in-cloud Eddy Dissipation Rate (EDR), which is a quantitative measure of turbulence. Comprehensive total lightning measurements are available in some regions of the United States such as in Northern Colorado and New Mexico. Herein, investigation of the temporal and spatial relationships of 3D total lightning and NTDA EDR measurements for non-severe single cell thunderstorms in New Mexico and severe storms in Colorado are described. Results suggest that the occurrence of moderate or greater turbulence at upper levels of storms is related to storm total lightning flash rate, though exact relationships depend on the storm type. Areas of moderate and greater turbulence are also observed to coincide with the footprint of horizontal lightning flash extents. Time series show that lighter turbulence begins to occur prior to lightning initiation in the storms and extends past the storm's lightning activity. Furthermore, trends of storm total moderate or greater turbulence are correlated to

storm total lightning flash rate and extent. These observations are consistent with other recent studies by the authors and others that suggest that total lightning may be useful in diagnosing areas of potentially hazardous atmospheric turbulence. With the expected advent of geostationary satellite-based lightning mapping in the next few years, possible relationships between lightning and turbulence characteristics might provide useful information to aviation users, particularly in oceanic or remote areas where ground-based Doppler weather radar observations are unavailable.

Deissler, R. G. and Boldman, D. R.

"TORNADOLIKE GRAVITY-DRIVEN VORTEX MODEL"

NASA TN D-7738, August 1974, Lewis Research Center, Cleveland, OH.

A study was made of the buoyancy-induced vorticity concentration produced as the fluid in a vortex accelerates vertically. The boiloff from liquid nitrogen, to which a small amount of initial vorticity was added, provided a source of cool, heavy gas in which a concentration of vorticity could take place. Condensation streamers made the flow visible. It was shown that the presence of a surface boundary layer is not necessary for an effective concentration of vorticity. A simple theoretical analysis of the phenomenon was also made. A radial contraction of the flow with vertical position and a characteristic hook shape in the top view of the streamlines were observed in both theory and experiment. The vorticity concentration observed herein may be similar to that which occurs in tornadoes.

Deissler, R. G. and Perlmutter, M.

"ANALYSIS OF THE FLOW AND ENERGY SEPARATION IN A TURBULENT VORTEX"

Journal of Heat Mass Transfer, Vol. 1, 1960, pp. 173-191.

An analysis is made of the velocity, temperature, and pressure distributions in a turbulent vortex with radial and axial flow. For making the calculations the vortex is divided into a core and an annular region, each with a different uniform axial mass velocity, although the equations obtained are applicable to an arbitrary axial mass velocity distribution. Tangential velocity, temperature, and pressure distributions, as well as curves for overall energy or temperature separation, are produced and compared with experiment. Using the analytical results, the causes of the energy separation are studied. It is concluded that the most important factor affecting the total temperature of a fluid element in a compressible vortex is the turbulent shear work done on or by the element.

Del Frate, J. H., Fisher, D. F. and Zuniga, F. A.

"IN-FLIGHT FLOW VISUALIZATION AND PRESSURE MEASUREMENTS AT LOW SPEEDS ON THE NASA F-18 HIGH ALPHA RESEARCH VEHICLE"

Proceedings of Fluid Dynamic Panel Symposium, Vortex Flow Aerodynamics, AGARD, CP-494, Scheveningen, The Netherlands, October 1990, pp. 13-1 to 13-42

In-flight results from surface and off-surface flow visualizations and from extensive pressure distributions document the vortical flow on the leading-edge extensions (LEX s) and forebody of the NASA F-18 high alpha research vehicle (HARV) for low speeds and angles of attack up to 50 deg. Surface flow visualization data, obtained using the emitted fluid technique, were used to define separation lines and laminar separation bubbles (LSB). Off-surface flow visualization data, obtained by smoke injection, were used to document both the path of the vortex cores and the location of vortex core breakdown. The location of vortex core breakdown correlated well with the loss of suction pressure on the LEX and with the flow visualization results from ground facilities. Surface flow separation lines on the LEX and forebody corresponded well with the end of pressure recovery under the vortical flows. Correlation of the pressures with wind-tunnel results show fair to good correlation.

del Pino, C., Lopez-Alonso, J. M. and Fernandez-Feria, R.

"DYNAMICS OF THE WING-TIP VORTEX IN THE NEAR FIELD OF A NACA 0012 AEROFOIL"

The Aeronautical Journal, Vol. 115, No. 1166, April 2011, pp. 229-239.

The dynamics of the wing tip vortex in the near field of a NACA 0012 airfoil has been analyzed by means of flow visualizations in a water tunnel. Different axial distances near the wing up to four chords. Reynolds numbers up to 42,000 and three angles-of-attack are studied to characterize the behavior of the vortex meandering. The spatio-temporal vortex center positions show distorted elliptical shapes in a (x,y)-plane. The Reynolds number has no significant influence on the axial evolution of the meandering amplitude. In addition, the flow visualizations obtained with a low-speed camera are analyzed by the singular value or proper orthogonal decomposition. Thus, the most energetic displacement modes are obtained. The frequency associated to these modes is computed by FFT. In all the cases studied, our results show that the most unstable mode corresponds to the azimuthal wavenumber $n=1$ in the so-called Kelvin helical modes and the frequency is lower or close to 1 Hz.

del Pino, C., Parras, L., Felli, M. and Fernandez-Feria, R.

"STRUCTURE OF TRAILING VORTICES: COMPARISON BETWEEN PARTICLE IMAGE VELOCIMETRY MEASUREMENTS AND THEORETICAL MODELS"

Physics of Fluids, Vol. 23, 2011, pp. 013602-1 - 013602-12.

The velocity field of the trailing vortex behind a wing at different angles of attack has been measured through the stereo particle image velocimetry technique in a water tunnel for Reynolds numbers between 20000 and 40000 for several distances to the wing tip. After filtering out the vortex meandering, the radial profiles of the axial and the azimuthal velocity components and of the radial profiles of the vorticity were compared to the theoretical models for trailing vortices by Batchelor and by Moore and Saffman, whose main features are conveniently summarized. We consider the downstream evolution of these profiles from just a fraction of the wing chord to more than ten chords. The radial profiles of the vorticity and the azimuthal velocity are shown to fit quite well to Moore and Saffman's trailing vortex model, while Batchelor's model does not fit so well, especially in the tails of

the profiles. At the downstream distances considered, the radial profiles of the axial velocity do not adjust so well to Moore and Saffman's model as the azimuthal velocity profiles do, but the disagreement with Batchelor's model is quite manifested, especially at the axis. Thus, the details of the flow structure are in better agreement with the predictions of Moore and Saffman's model. The downstream evolution of several key features of the measured velocity profiles is also in agreement with the predictions of Moore and Saffman's model, within the dispersion of the experimental data, but up to the largest axial distance considered in this work we cannot decide if they follow the asymptotic behavior predicted by this model.

Delaney, B. T.

"AIRCRAFT VORTEX EFFECTS ON GROUND LEVEL POLLUTANT CONCENTRATION AND TRACKING OF VORTEX MOVEMENT IN THE AIRPORT ENVIRONMENT"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 264-282

The effect on ground level pollutant concentrations of including a mechanism to consider the transport of aircraft-generated pollutants captured in the trailing vortex system is examined by coupling a three-dimensional vortex transport program with a line source dispersion routine. It was found that not only would the ground level concentrations of oxides of nitrogen change but so would the spatial distribution. Echoes recorded by a FM-CW radar are shown to be the result of water vapor and pollutants trapped in a descending vortex system.

Delaney, B. T. and Ledbetter, J. O.

"AIRCRAFT VORTEX EFFECTS ON GROUND LEVEL POLLUTANT CONCENTRATION"

Air Pollution Control Assoc., Paper 77-41,5, Toronto, Canada, June 1977

The effect of aircraft wake vortex transport on airport air pollution models is assessed. In particular, the emission of nitrogen oxides by aircraft during one segment of the takeoff phase (i.e., during the first 943 m of climb) is not adequately simulated by models adopted by the U.S. Air Force and the Environmental Protection Agency. In a study conducted at a major airport, inclusion of the effects of a rolled up contrarotating vortex pair generated by aircraft in the takeoff phase is found to improve the nitrogen oxides prediction capability of a conventional airport air quality model.

Delaney, B. T., Noonkester, R. V. and Ledbetter, J. O.

"REMOTE SENSING OF AIRCRAFT WAKE VORTEX MOVEMENT IN THE AIRPORT ENVIRONMENT"

Air Pollution Control Assoc., Paper 77-41,4, Toronto, Canada, June 1977

The use of FM-CW radar to track aircraft wake vortices at airports is discussed; remote tracking of vortices may aid in studying ground level pollution dispersion and the effects of vortex trails on

encountering aircraft. Results are reported for a month-long test of a FM-CW radar system placed at the edge of a runway at Lindbergh Field, San Diego. V-echoes detected by the FM-CW radar appear to reflect the water and/or exhaust products trapped in the descending vortex trails of aircraft departing from the runway. Thus FM-CW radar detection seems a possible alternative to vortex sensing systems based on acoustic energy, anemometers, or laser backscatter.

Delaplace, F.

"METHOD AND DEVICE FOR REDUCING THE WAKE VORTICES OF AN AIRCRAFT IN THE APPROACH/LANDING PHASE"

US Patent Application 2007/0170313 A1, July 2007.

According to the invention, the spoilers are automatically ordered to deploy when the lift-augmenting aerodynamic surfaces are themselves ordered to deploy and are automatically ordered to retract when at least one of the following three conditions holds: the angle of incidence of the aircraft is equal to or greater than an incidence threshold; the speed of the aircraft is equal to or less than a speed threshold; and the aircraft is instigating a go-around maneuver.

Delbende, I. and Chomaz, J.-M.

"NONLINEAR CONVECTIVE/ABSOLUTE INSTABILITIES IN PARALLEL TWO-DIMENSIONAL WAKES"

Physics of Fluids, Vol. 10, No. 11, November 1998, pp. 2724-2736

The linear versus nonlinear convective/absolute instability of a family of plane wake profiles at low Reynolds number is investigated by numerically comparing the linearized and the fully nonlinear impulse responses. Through an analysis of the linear flow response obtained by direct numerical simulation (DNS), the linear temporal and spatiotemporal instability properties are retrieved, in excellent agreement with the properties obtained by Monkewitz (1994) from the study of the associated viscous dispersion relation. Nonlinear terms are then shown to limit the amplitude to a saturation level within the response wave packet, while leaving the trailing and leading edges unaffected. For this family of open shear flows, the velocities of the fronts, formed between the trailing or leading edge and the central saturated region, are thus selected according to the linear Dee and Langer criterion (1983), whereas the front solutions are fully nonlinear. This property may be of importance in justifying the use of linear instability properties to predict the onset and the frequency of the von Karman vortex street, as determined by Hammond and Redekopp (1997).

Delbende, I., Chomaz, J.-M. and Huerre, P.

"ABSOLUTE/CONVECTIVE INSTABILITIES IN THE BATCHELOR VORTEX: A NUMERICAL STUDY OF THE LINEAR IMPULSE RESPONSE"

J. Fluid Mechanics, Vol. 355, 1998, pp. 229-254

The absolute/convective instability properties of the Batchelor vortex are determined by direct numerical simulation of the linear impulse response. A novel decomposition procedure is applied to the computed wavepacket to retrieve the complex wavenumber and frequency prevailing along each spatio-temporal ray. In particular, the absolute wavenumber and frequency observed in the laboratory frame are determined as a function of swirl parameter and external flow. The introduction of a moderate amount of swirl is found to strongly promote absolute instability. In the case of wakes, the transitional helical mode that first undergoes a switch-over to absolute instability is found to be $m = -1$ without requiring any external counterflow. In the case of jets, the transitional helical mode is very sensitive to swirl and varies in the range $-5 \leq m \leq -1$. Only a slight amount of external counterflow (1.5% of centerline velocity) is then necessary to trigger absolute instability. The results of this numerical procedure are in good qualitative and quantitative agreement with those obtained by direct application of the Briggs-Bers criterion to the inviscid dispersion relation (Olendraru et al. 1996). Implications for the dynamics of swirling jets and wakes are discussed.

Delbende, I., Gomez, T., Josserand, C., Nore, C. and Rossi, M.

"VARIOUS ASPECTS OF FLUID VORTICES"

Comptes Rendus Mecanique, Vol. 332, Issue 9, September 2004, pp. 767-781

A general review of the current research in vortex dynamics is presented, based on contributions given during a workshop held in May 2003 at Porquerolles, France. This article aims at providing a picture of the work performed on this subject in the French community. Various cases are covered, from 2D vortex patches to 3D vortex tubes; from isolated vortices to shear flows. Different contexts are considered: pure Euler and Navier-Stokes flows as well as stratified, rotating and magnetic flows.

Delbende, I., Rossi, M. and Le Dizès, S.

"STRETCHING EFFECTS ON THE THREE-DIMENSIONAL STABILITY OF VORTICES WITH AXIAL FLOW"

J. Fluid Mech., Vol. 454, March 2002, pp. 419-442

The effect of stretching on the three-dimensional stability of a viscous unsteady vortex is addressed. The basic flow, which satisfies the Navier-Stokes equations, is a vortex with axial flow subjected to a time-dependent strain field oriented along its axis. The linear equations for the three-dimensional perturbations of the stretched vortex are first reduced by using successive changes of variables to equations which are almost identical to those of the unstretched vortex but with time-dependent parameters. These equations are then numerically solved in the particular case of the Batchelor vortex with a strain field which first compresses then stretches the vortex. Through this simulation, it is qualitatively demonstrated how the simultaneous action of stretching and azimuthal vorticity may destabilize a vortex. It is also argued that it provides a possible mechanism for the vortex bursts observed in turbulence experiments.

Delery, J. and Horowitz, E.

"INTERACTION BETWEEN A SHOCK-WAVE AND A VORTEX FLOW"

Fluid Dynamics Panel Symposium, AGARD-CP-342, April 1983, Rotterdam, Netherlands, pp. 5-1 - 5-9.

The interaction between a vortex and a shock-wave normal to the streamline axis of the vortex has been studied both experimentally and theoretically. Measurements have been made for four values of the upstream Mach number ranging from 1.6 to 2.28. They allowed the characterization of the shock effect on the vortical flow structure when breakdown does not occur. They also led to the definition of a breakdown limit function of the two parameters: normal shock strength - vortex swirl/ratio. Two flow configurations associated respectively with interaction without and with vortex bursting have been carefully probed by using a two-color LDV system. When breakdown occurs, the mean meridian motion comprises a 'recirculating bubble' near the axis of the structure. A flow model has been developed in the framework of the Euler equations. As long as the vortex does not burst, the calculations thus made give a faithful description of flow phenomena. They also predict a limit for vortex breakdown which agrees satisfactorily with experiment. [In French].

Delery, J. M.

"SEPARATION AND VORTEX FORMATION IN TURBULENT FLOWS"

2nd Caribbean Conf. on Fluid Dynamics, Jan. 1992, Trinidad, West Indies.

Separation in three-dimensional flows leads to the formation of vortical structures resulting from rolling up of the viscous flow 'sheet', initially contained in a thin boundary layer, which springs up from the surface into the outer perfect fluid flow. A clear physical understanding of this phenomenon must be based on a rational analysis of the flow field structure using the critical-point theory. With the help of this theory it is possible to correctly interpret the surface flow patterns which constitute the imprints of the outer flow and to give a rational and coherent description of the vortical system generated by separation. This kind of analysis is applied to separated flows forming on typical obstacles, the field of which has been thoroughly studied.

Delery, J. M.

"PHYSICS OF VORTICAL FLOWS"

Journal of Aircraft, Vol. 29, No. 5, Sept.-Oct. 1992, pp. 856-876.

Separation in three-dimensional flows leads to the formation of vortical structures resulting from rolling up of the viscous flow 'sheet' initially contained in a thin boundary layer, which springs up from the surface into the outer perfect fluid flow. A clear physical understanding of this phenomenon must be based on a rational analysis of the flow field structure using the critical-point theory. With the help of this theory, it is possible to interpret correctly the surface flow patterns that constitute the imprints of the outer flow and to give a rational and coherent description of the vortical system generated by separation. This kind of analysis is applied to separated flows forming on typical obstacles, the field of

which has been thoroughly studied by means of visualizations and probing using multi-hole pressure probes and laser velocimetry. Thus, the skin friction line patterns of a transonic channel flow and of a multibody launcher are interpreted. Then, the vortical systems of a delta wing and an afterbody at an incidence are considered. The last two configurations are a missile fuselage-type body and an oblate ellipsoid.

Delery, J. M.

"ASPECTS OF VORTEX BREAKDOWN"

Prog. Aerospace Sci., Vol. 30, No. 1, March 1994, pp. 1-59

Carefully executed visualizations and velocity measurements have allowed a clear description of the field associated with breakdown. These experiments executed in a vortex tube, where the vortex is confined, or in arrangements where it is free, show that the existence of a stagnation point forming on the centerline of the vortical structure is a distinctive feature of breakdown. Different types of break down (spiral and bubble types) seem to exist, however this point is subject to controversy. At the same time, the vortex undergoes a brutal dilatation with the generation of large-scale fluctuations.

Delery, J., Horowitz, E., Leuchter, O. and Solignac, J.-L.

"FUNDAMENTAL STUDIES ON VORTEX FLOWS"

La Recherche Aerospatiale, No. 2, 1984, pp. 1-24.

Subsonic and supersonic flows are investigated in a study concerning vortex flows subjected to the destabilizing effect of an adverse pressure gradient. For the subsonic condition, two modes of vortex generation are considered: a vortex created by the rolling up of two vertical sheets coming from the trailing edge of two vanes mounted on a cylindrical string, and a vortex which is produced by a delta wing with an angle of attack. During supersonic flow tests, much attention is focused on the interaction between a normal shock wave and vortex whose streamwise axis is perpendicular to the shock. The data obtained on flows in subsonic and supersonic conditions, using conventional pressure probes and two-color laser velocimetry, gives a description of the vortex's mean and turbulent properties which evolve toward breakdown. In both subsonic and supersonic tests, a limit on the vortex breakdown could be defined experimentally as a function of parameters measuring the intensity of the destabilizing pressure gradient, and the vortex strength. For the shock wave/vortex interaction, this limit can be predicted using a no-flow model in which the Euler equations are solved by a time-marching method.

Delisi, D.

"CROW INSTABILITY IN HIGH AND LOW REYNOLDS NUMBER LABORATORY EXPERIMENTS, DEPENDENCE ON THE ENVIRONMENT, AND COMPARISONS TO FULL-SCALE MEASUREMENTS"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008.

Crow instability transforms two-dimensional vortex wakes, such as those generated by aircraft wingtips and flaps, into three-dimensional vortex rings. It was commonly believed that these 3D vortex rings, once generated, rapidly decay and dissipate. Through a series of laboratory experiments, we will examine how this instability evolves with ambient stratification, turbulence, shear, and a combination of turbulence and shear. Whenever possible, we will compare these experiments to full-scale measurements obtained at Denver and elsewhere.

Delisi, D. P.

"LABORATORY MEASUREMENTS OF THE EFFECT OF AMBIENT TURBULENCE ON TRAILING VORTEX EVOLUTION"

AIAA Paper No. 2006-1078, Reno, NV, January 2006

We have repeated the laboratory experiments of Sarpkaya and Daly, using different wings and different flow visualization techniques. Our results show that, although our vortices link at the same nondimensional times as those of Sarpkaya and Daly, the vortices do not die, but, instead, continue migrating as vortex rings, much as they would in a flow with no ambient turbulence. We also measured the turbulence levels between the vortex cores of both laboratory vortices and behind a C-130 aircraft. These turbulence levels were larger than many atmospheric turbulence levels, with normalized turbulent velocity dissipation rates greater than 0.3 within nondimensional times. Our conclusion is that, for nondimensional turbulent velocity dissipation rates less than ~ 0.3 , ambient turbulence has a large effect on when vortices from a wing link into rings, but may have little effect on their decay.

Delisi, D. P.

"LABORATORY STUDIES OF MASS TRANSPORT BY AIRCRAFT WAKE VORTICES"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

Aircraft engine exhaust can be transported vertically from one altitude to another by the counter-rotating vortices generated by the wing. In this paper, we present vortex transport laboratory measurements made in a water-filled towing tank. The vortices were generated by towing a wing down the tank at a constant angle of attack and a constant depth below the surface. The wing was towed through a cloud of particles, some of which became entrained into the vortex system. As the vortices migrated vertically, many particles remained in the vortex cell while some of the particles detrained from the cell. By counting the number of particles detrained and the total number of particles in the system, we can calculate the percent of particles left in the ring as a function of the vertical distance from the generation point. Measurements of vortex transport in both non-stratified and stratified flows will be presented as well as comparisons to published flight data.

Delisi, D. P.

"LABORATORY MEASUREMENTS OF THE CIRCULATION DECAY OF VORTICES GENERATED FROM A LIFTING WING"

AIAA Paper 2011-3034, June 2011, Honolulu, Hawaii.

Circulation measurements of the vortices generated behind a wing are made in both unstratified and stratified water. The circulations are measured in both the two-dimensional line vortices which evolve immediately behind the wing and in the three-dimensional ring vortices which evolve from the line vortices. The measurements show that the circulation decay of the vortices is faster in a stratified fluid than in an unstratified fluid, as expected. The circulations of the line vortices were measured in a plane perpendicular to the direction of motion of the wing. The circulation of the ring vortices was initially measured in a plane parallel to the direction of motion of the wing. Because these two measurement planes are perpendicular to each other, the circulations of ring vortices in an unstratified fluid were also measured in the plane perpendicular to the motion of the wing, that is, in the same measurement plane as the line vortices. These two sets of circulations of the ring vortices, in a plane perpendicular to the motion of the wing and in a plane parallel to the motion of the wing, are shown to be similar. For all the measurements, the circulation decay of vortex rings is shown to be about three times slower than the circulation decay of the line vortices. Finally, the circulations of the line vortices in a stratified fluid, with a Froude number of around 6, are shown to be consistent with measurements of circulations of aircraft vortices out of ground effect in an atmosphere with the same Froude number. This consistency suggests that laboratory measurements of the vortices behind lifting wings may, at least in some cases, be applicable to full-scale aircraft vortices.

Delisi, D. P. and Greene, G. C.

"MEASUREMENTS AND IMPLICATIONS OF VORTEX MOTIONS USING TWO FLOW-VISUALIZATION TECHNIQUES"

J. Aircraft, Vol. 27, No. 11, November 1990, pp. 968-971

The new, laboratory wake measurements presented here are significant in their own right; however, the authors believe these results and the implications of incorporating different visualization techniques may be of interest to researchers studying other aircraft vortex flows. The evolution and migration of vortices is applicable to a wide class of aerospace problems. The data presented here point out the deficiencies in our current understanding of vortex motions. The evolution is even less well understood if we include ground effect, wind, and other environmental factors.

Delisi, D. P. and Greene, G. C.

"EXPERIMENTAL MEASUREMENTS OF THE EVOLUTION OF A VORTEX PAIR IN A NONSTRATIFIED FLUID, PART 1: MIGRATION AND PERSISTENCE"

AIAA Paper No. 2009-0345, January 2009, Orlando, FL.

Laboratory measurements of the evolution of a vortex pair from a lifting wing in a non-stratified, nonturbulent, and unsheared fluid are presented. The new aspect of these measurements is that we have been able to follow vortex evolution from generation through decay in three stages: (1) a two-dimensional line vortex pair, (2) transition from two-dimensional to three-dimensional vorticity, and (3) development, migration, and decay of vortex rings. In non-dimensional units of time, T , the first stage is shown to last until T about 5, the second stage from T about 5 to about 10, and the third stage from T about 10 to at least 60 or more. In non-dimensional units of migration distance, the vortices were observed to propagate up to or beyond $H = 20$. Measurements were initially obtained using model laboratory wings. These wings had an aspect ratio of around 2, chord Reynolds numbers ranging from 41,000 to 124,000, and lift coefficients of around 1.0. Because the laboratory results were significantly different from previously reported results, we conducted tests on a larger-scale wing in a lake to determine if facility effects or laboratory flow visualization methods were a significant factor in the laboratory observations. In the lake study, we used a multi-element airfoil with an aspect ratio of around 1.7, a chord Reynolds number of 2,600,000, and a lift coefficient of 1.38. Results from the lake tests are presented which confirm the non-dimensional migration results of the laboratory study. This paper presents migration and persistence results. A companion paper (Part 2) presents detailed measurements of the low Reynolds number wings used in this study and measurements of the near- and far-wake vortex evolution.

Delisi, D. P. and Greene, G. C.

"EXPERIMENTAL MEASUREMENTS OF THE EVOLUTION OF A VORTEX PAIR IN A NONSTRATIFIED FLUID, PART 2: LOW REYNOLDS NUMBER WINGS AND VORTEX WAKE CHARACTERISTICS"

AIAA Paper No. 2009-0346, Jan. 2009, Orlando, FL.

Laboratory measurements of low Reynolds number 3-D wings and vortex wakes generated by the wings were obtained in a water-filled towing tank. Detailed measurements follow the vortices from near generation through vortex reconnection and the evolution and migration of vortex rings. Studies were performed with the wings at various distances below the water surface. Measurements show that the magnitude of lift generated decreases as the wing is towed closer to the water surface. The lift approaches the lift at deep depths for trailing edge depths below the surface of three chords or more. Measurements of wing characteristics show that cambered plate wings are more efficient generators of lift than conventional airfoil shapes at the Reynolds numbers of the experiments, where the chord Reynolds numbers range from around 40,000 to around 164,000. Near-field vortex measurements show that the initial velocity of the vortex system is well predicted from measurements of lift and the initial vortex separation. Near-field axial velocity measurements behind the wings are also presented and show an initial jet velocity in the core followed by a velocity defect. Measurements of the sinusoidal, or Crow, instability show that the most unstable wavelength, on average, is shorter than that predicted by Crow. Measurements of the distance between vortex rings as well as vortex ring diameters are also presented. Far-field vortex measurements show that there is considerable variability in the angle vortex rings make to the vertical. Because of this variability, many vortex rings merge as they migrate, resulting in fewer rings with increasing vertical distance from the ring. It is suggested that the variability in the angle of migration is caused by variability in vortex reconnection.

Delisi, D. P. and Lai, D. Y.

"DETRAINMENT FROM A VORTEX PAIR IN A NONSTRATIFIED FLUID"

AIP Conference Proceedings, Vol. 1376, 2011, pp. 311-313.

Laboratory experiments of detrainment from a vortex pair are reported to better understand and numerically model the evolution of aircraft trailing wake vortices. The vortex pair was generated by towing a model wing down a water-filled, unstratified towing tank at an angle of attack. Nearly neutrally buoyant particles were introduced into the vortex cell or into the vortex core. The detrainment of fluid from the vortex cell is shown to be faster than the detrainment from the vortex core.

Delisi, D. P. and Pierce IV, W. P.

"CIRCULATION MEASUREMENTS OF MERGING VORTEX RINGS"

AIAA Paper No. 2011-3033, June 2011, Honolulu, Hawaii.

Circulation measurements of merging vortex rings were performed in an unstratified fluid to determine the circulation loss during vortex reconnection. The rings were generated by pistons, aligned with a 15-degree difference between the two propagation directions. Circulation measurements were made in two measurement planes. A front view plane, in the plane of the generators and the centers of the two vortex rings, was used to measure the circulations of the vortex rings before reconnection. A side view plane, oriented symmetrically between the generators and orthogonal to the front view plane, was used to measure the circulations of the vortex rings emerging from the reconnection. The circulations of both laminar and turbulent vortices were measured. The measurements show that over 90% of the circulation is conserved during the reconnection of both laminar and turbulent vortex rings. Thus, almost no circulation was lost (beyond natural single-ring decay) between the vortices that disappeared in the front view and reappeared in the side view for either laminar or turbulent vortex rings. These results suggest that, while the vortex cells may be laminar or turbulent, their cores are laminar and reconnection is essentially a laminar process. These results also suggest that when aircraft line vortices evolve into vortex rings, when the flow is unstratified, the circulations of these rings will be nearly the same as the circulations of the line vortices before reconnection.

Delisi, D. P. and Robins, R. E.

"DEVELOPMENT OF WAKE VORTEX PREDICTION ALGORITHMS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 469-488

Wake vortex prediction algorithms are developed that model the essential physics; handle atmospheric parameters; handle out-of-ground effect, near ground effect, and in-ground effect; and

runs quickly on a PC or workstation. In this project the following tasks are performed: (1) Predictor algorithm results have been compared with data for vortices in and out of ground effect; (2) Algorithm works reasonably well but needs refinement; and (3) Current predictor algorithm will be used at DFW.

Delisi, D. P. and Robins, R. E.

"EFFECTS OF CROSSWIND SHEAR ON TRAILING VORTEX EVOLUTION"

AIAA Paper No. 2006-1075, Reno, NV, January 2006

Wake vortices from aircraft evolve in a local atmosphere that may contain stratification, and/or turbulence, and/or wind. Previous investigations have studied the effects of ambient stratification and turbulence on wake vortex evolution, but the effects of wind, and, more specifically, wind shear, defined as the vertical change of the horizontal wind, are less well understood. In this study, we used laboratory experiments and numerical simulations to examine the effects of shear on the evolution of wake vortices. It is found that the second derivative of the crosswind profile is the important parameter in determining the vertical position of the vortices and the angle of tilt of a line joining the vortex cores. A concave shear profile tilts the vortices in one direction while a convex profile tilts the vortices in the other direction. The stronger the shear gradient, the larger the vortex tilt, and the slower the vertical migration speed of the vortex pair through the shear gradient, the larger the vortex tilt. The tilt of the vortex cores begins when the vortex cell first enters the region where the shear gradient is non-zero, and the tilt stops changing when the vortex cell leaves the region where the shear gradient is non-zero. Thus, the shear gradient affects the entire vortex cell, not just the vortex cores. The numerical simulations predict quite well the observed vertical descent and the tilt of the vortex cores observed in the laboratory experiments.

Delisi, D. P. and Robins, R. E.

"VORTEX EVOLUTION IN REALISTIC GEOPHYSICAL FLOWS"

NWRA-CR-93-R083, July 1996, Northwest Research Associates, Bellevue, WA.

Laboratory experiments and numerical simulations of vortex evolution in realistic geophysical flows are reported. Two laboratory experiments are discussed. The first experiment examined three-dimensional vortices produced from a wing in a non-stratified non-sheared flow. This study showed that vortices can migrate farther and last longer than previously reported. The second laboratory experiment investigated the evolution of two-dimensional vortices in a stratified flow shear flow. This experiment showed the evolution of a 'solitary' vortex when the background Richardson number was around four or less. Circulation estimates were also obtained for these vortices and showed a more rapid decay of circulation of the countersign vortex. Two numerical studies are also reported. In the first numerical study, we examined the evolution of a two-dimensional vortex pair in a stratified shear flow. This study showed that the vortex pair evolved into a solitary vortex when the ambient Richardson number was on the order of unity or less. A second numerical study used a k-e model to examine the evolution of a two-dimensional vortex pair. It was found that the standard k-e model did a

poor job of representing the turbulent dissipation in vortex flows. Good agreement with experimental results was obtained with this model with a reduction in the eddy viscosity coefficient.

Delisi, D. P. and Robins, R. E.

"SMALL-SCALE INSTABILITIES IN TRAILING WAKE VORTICES IN A STRATIFIED FLUID"

AIAA Paper No. 1997-1784, Snowmass Village, CO, June 1997.

We have examined the behavior of wake vortices in density-stratified fluids, both in laboratory experiments and by using a three-dimensional numerical code. In an unstratified fluid, the primary instability is the Crow instability, which has a characteristic initial wavelength of around $8.6B$, where B is the initial separation distance between the vortices. In stratified fluids at late times, we have observed an instability with a shorter wavelength of around $1-2B$. This instability appears at a time in the evolution of the vortices when the vertical migration nearly has reached its maximum extent. For a commercial aircraft, the vertical peak-to-peak amplitude due to this instability could be greater than 75 ft.

Delisi, D. P. and Robins, R. E.

"OBSERVATIONS AND PREDICTIONS OF TRAILING WAKE VORTEX EVOLUTION FOR AIRCRAFT AND LABORATORY MODELS"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 73-75

Wake vortex evolution is investigated using a wake vortex prediction algorithm, observations of aircraft wakes, and laboratory measurements behind model wings. The prediction algorithm in the out-of-ground effect (OGE) region is based on the original algorithm presented by Greene, with modifications for variable stratification and cross wind. The algorithm uses unrestrained point vortices for the near-ground effect and in-ground effect (IGE) regions. Countersign vorticity is modeled in the IGE region using multiple secondary vortices. The aircraft data were obtained under the NASA AVOSS Program at Memphis International Airport with the MIT/Lincoln Laboratory lidar sensor. The lidar measurements contain temporal information on both vortex location and circulation. The circulation estimates have been corrected to account for both vortex descent and drift. Laboratory data were obtained using model wings in a water-filled towing tank. Digital Particle Imaging Velocimetry was used to estimate vortex circulations and trajectories. Ensemble aircraft measurements from 25 Boeing-727 aircraft in the OGE region show circulation decay and a nearly constant vortex radius for more than 100 seconds after aircraft passage. The vortex trajectory and circulation estimates from the aircraft compare well to similar measurements from laboratory vortices with comparable Froude numbers. Both the aircraft and laboratory measurements are compared to estimates from the prediction algorithm.

Delisi, D. P. and Robins, R. E.

"VORTEX EVOLUTION AND CHARACTERIZATION"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

A major concern with airport capacity issues is the characterization and evolution of trailing wake vortices. These vortices can be studied with laboratory models, numerical simulations, and aircraft measurements. An issue with using laboratory studies is how the difference in Reynolds number affects the results and the interpretations of those results. The danger is that effects that are observed in low-Reynolds number flows may not be observed in high-Reynolds number aircraft flows. Consequently, care must be used in interpreting low-Reynolds number studies and extrapolating those results to the high-Reynolds number aircraft case. For several years, we have been performing low-Reynolds number laboratory model studies and comparing those results to aircraft data and numerical simulations. Favorable comparisons of laboratory vortices with aircraft vortices and numerical simulations have included vortex migration, in both non-stratified and stratified environments, vortex core size with time after aircraft passage, vortex circulation as a function of time after aircraft passage, and the level of turbulence in the vortex cell. In addition, we have performed several laboratory studies with which we have no full-scale data for comparison. These studies include vortex separation with time and vortex lifetime in both quiescent and turbulent backgrounds.

Delisi, D. P. and Robins, R. E.

"SHORT-SCALE INSTABILITIES IN TRAILING WAKE VORTICES IN A STRATIFIED FLUID"

AIAA Journal, Vol. 38, No. 10, October 2000, pp. 1916-1923

Measurements of the evolution of wingtip trailing wake vortices in nonturbulent and unsheared density-stratified fluids are reported, using both laboratory experiments and a three-dimensional numerical code. As is widely known, and as our laboratory and numerical results confirm, the primary instability for these vortices in an unstratified fluid is the Crow instability, which has a characteristic initial wavelength of around $8.6B$, where B is the initial separation distance between the vortices. In stratified fluids, however, our laboratory observations and numerical simulations show an instability with a shorter wavelength of around $B-2B$. This instability appears at a time in the evolution of the vortices when the vertical migration nearly has reached its maximum extent. The observed instability grows both in amplitude and wavelength with time. When the vortex Froude number is around one, the instability first becomes visible at a nondimensional time T of around 2 and reaches a maximum at T of around 4. For a commercial aircraft, the latter time corresponds to distances of around 10-25 km behind the aircraft. In flight, at $T \sim 4$, the vertical peak-to-peak amplitude oscillation of the vortex cores due to this instability could be up to 20 m with a horizontal wavelength around 100 m.

Delisi, D. P., Greene, G. C. and Robins, R. E.

"COMPARISON OF LABORATORY WAKE VORTICES WITH AIRCRAFT VORTICES"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

Measurements of wake vortices from both laboratory models and aircraft will be presented. The laboratory measurements were obtained in a water-filled towing tank using model wings. Vortex evolution in the laboratory is followed from generation through decay in three stages: (1) a 2-D line vortex pair, (2) transition from 2-D line vortices to 3-D vortex rings, and (3) development, migration, and decay of vortex rings. The laboratory experiments use both dye (for visualization) and neutrally-buoyant particles (for both visualization and DPIV measurements of circulation). We will present measurements in both non-stratified and stratified flows to show the effects of stratification. Measurements of aircraft vortices, obtained as part of NASA's AVOSS Wake Vortex Program, will also be presented. Simultaneous meteorological measurements will be used to interpret the aircraft wake vortices in terms of nondimensional parameters. We will compare vortex transport and decay from the laboratory and aircraft measurements both to each other and to a modified version of a wake vortex prediction algorithm originally reported by Greene (1986).

Delisi, D. P., Greene, G. C. and Tittsworth, J.

"GEM4D, A GENERAL VORTEX ENCOUNTER MODEL WITH 4 DEGREES OF FREEDOM: FORMATION, VALIDATION, AND USE"

AIAA Paper 2018-3020, June 2018, Atlanta, GA.

A fast, versatile, and easy to run wake vortex encounter model has been developed and tested. The model is called GEM4D for General vortex Encounter Model with 4 Degrees of Freedom. GEM4D uses a straight, unswept wing with a linear taper and classical aerodynamic strip theory. The model includes the X, Y, and Z directions and roll but does not include pitch or yaw effects. The results from GEM4D have been compared to results from both 6-Degree of Freedom Full Flight Simulators and from field data of wake vortex encounters. Four examples of these comparisons are shown, and include a range of aircraft size and vortex strength. In all the comparisons performed, using the results from the simulator tests and field encounters as 'truth' GEM4D reproduced the maximum roll (bank) angles from these encounters with differences from near zero to around 20 percent. Thus, GEM4D appears to contain all or most of the essential physics of a wake vortex encounter.

Delisi, D. P., Greene, G. C., Robins, R. E. and Singh, R.

"RECENT LABORATORY AND NUMERICAL TRAILING VORTEX STUDIES"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 34-1 to 34-10.

Results from two laboratory studies and two numerical studies are presented. In the first laboratory study, measurements of the strength of vortices from a three-dimensional (3-D) model wing are presented. The measurements follow the vortices as they evolve in time from a two-dimensional (2-D) line vortex pair to the development and migration of 3-D vortex rings. It is shown that the resulting vortex rings can contain up to 40 percent of the initial vortex circulation. Thus, the formation of vortex

rings may not necessarily signal the end of the wake hazard to following aircraft. In the second laboratory study, we present the results of an experiment which shows how the spanwise drag distribution affects wake-vortex evolution. In the first numerical study results of 3-D numerical calculations are presented which show that the vortex Reynolds number has a significant influence on the evolution and migration of wake vortices. When the Reynolds number is large, 3-D vortex rings evolve from the initially 2-D line vortex pairs. These vortex rings then migrate vertically. When the Reynolds number is lower, the transition of vorticity from 2-D to 3-D is delayed. When the Reynolds number is very low, the vortices never transition to 3-D, and the vertical migration is significantly reduced. It is suggested that this effect may have been important in previous laboratory wake-evolution studies. A second numerical study shows the influence that vertical wind shear can have on trailing vortex evolution.

Delisi, D. P., Greene, G. C., Robins, R. E., Vicroy, D. C. and Wang, F. Y.

"AIRCRAFT WAKE VORTEX CORE SIZE MEASUREMENTS"

AIAA Paper No. 2003-3811, Orlando, FL, June 2003.

We have examined data from three aircraft field tests designed, in part, to measure the size of the vortex cores generated by the aircraft. The field tests were performed between 1990 and 1997 at Idaho Falls, ID, Wallops Island, VA, and John F. Kennedy International Airport (JFK) in NY. At Idaho Falls, an instrumented 200-foot tower was used to measure velocities in the wakes of Boeing 727, 757 and 767 aircraft flown upwind of the tower. In the Wallops Island test, velocities and smoke trails behind a Lockheed-Martin C-130 aircraft were measured by an instrumented North-American Rockwell OV-10 aircraft flown behind the C-130. For the JFK tests, the vortex wakes of landing aircraft were measured by a Continuous Wave lidar operated by MIT/Lincoln Laboratories. The results from all three field tests are quite consistent, and suggest that the size of the velocity cores in trailing vortices behind an aircraft is on the order of one percent of the wingspan of the aircraft, where core size is defined as the radial distance from the vortex center to the point of maximum tangential velocity. We note that numerical simulations of trailing vortex evolution typically use velocity vortex core sizes in the range from five to twelve percent of the wingspan of an aircraft. Thus, the values of velocity core size used in numerical models are significantly larger than the full-scale values reported here. We also show that a typical size of smoke trails, where smoke is used to visualize the vortices behind an aircraft, is approximately twice the size of the velocity core.

Delisi, D. P., Pruis, M. J., Jacob, D. and Lai, D. Y.

"FIRST RESULTS FROM THE NASA WAKE VORTEX MEASUREMENTS AT THE MEMPHIS INTERNATIONAL AIRPORT"

AIAA Paper 2014-2467, June 2014, Atlanta, GA.

New measurements of aircraft wake vortices and concurrent meteorological measurements are being made at the Memphis International Airport by NorthWest Research Associates, Inc., with the support

of Coherent Research Group, LLC, under the National Aeronautics and Space Administration Airspace Systems Program. The meteorological measurements began in March 2013 and are continuing today. These measurements consist of vertical temperature profiles, point wind and temperature measurements, and supporting meteorological measurements (rain, pressure, etc.). In addition, a Halo Photonics StreamLine lidar has been used since April, 2013 to provide vertical profiles of wind speed and direction. Finally, a Lockheed Martin Coherent Technology (LMCT) WindTracer lidar, owned and operated by Arizona State University, has been used since June, 2013. Both the LMCT lidar and the Halo Photonics lidar have been used to measure aircraft wake vortices and to provide additional wind information. These measurements are being used to characterize the evolution of aircraft wake vortices generated in ground effect and to correlate those measurements with atmospheric conditions. The first results from these measurements that show the dependence of wake evolution on atmospheric conditions are presented.

Delisi, D. P., Pruis, M. J., Wang, F. W. and Lai, D. Y.

"ESTIMATES OF THE INITIAL VORTEX SEPARATION DISTANCE, B-ZERO, OF COMMERCIAL AIRCRAFT FROM PULSED LIDAR DATA"

AIAA Paper 2013-0365, January 2013, Grapevine, TX.

An aircraft in flight generates multiple wake vortices, the largest of which are a result of the lift on the wings. These vortices rapidly roll up into a counter-rotating vortex pair behind the aircraft. The initial separation between the centroids of vorticity behind the aircraft, or the cores of the resulting vortex pair, is commonly denoted as b-zero. This separation distance is used to estimate the initial vortex strength (circulation) and to nondimensionalize both time and circulation behind the aircraft. Thus, b-zero is an important parameter in nondimensionalizing aircraft wake measurements. For an elliptically loaded wing, $b\text{-zero} = (\pi/4)s$, where s is the wingspan of the generating aircraft. The initial descent velocity of the vortex system behind the aircraft, $V\text{-zero}$, is proportional to $1/b\text{-zero}^2$. Thus, from estimates of $V\text{-zero}$ from lidar measurements, we can estimate b-zero. Estimates of $V\text{-zero}$ from lidar measurements of vortex altitude vs. time are presented in the Out of Ground Effect (OGE) region for aircraft arriving at Denver International Airport and San Francisco International Airport. Estimates of b-zero for these aircraft are then obtained. These measurements suggest that, while some estimates of b-zero from commercial aircraft are close to the value based on elliptical wing loading, some aircraft have distinctly nonelliptical values of b-zero.

Delisi, D. P., Robins, R. E. and Altman, D. B.

"LABORATORY AND NUMERICAL STUDIES OF VORTEX EVOLUTION IN IDEAL AND REALISTIC ENVIRONMENTS"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 30-1 - 30-28

Laboratory and numerical results are presented for the evolution of aircraft vortices. The laboratory results, for vortices from a rectangular wing towed in a non-stratified, water-filled tank, show that organized vorticity migrates much farther and lasts significantly longer than shown in previous studies. The differences between our results and results from previous studies are attributed to differences in flow visualization techniques. Numerically, we use a 2-D code to simulate full-scale measurements from a Boeing-747 aircraft in ground effect and to investigate the vortex hazard generated by a Boeing-767 aircraft near touchdown on landing. Measured stratification and cross-track winds are included in both numerical simulations. The numerical results show that full-scale measurements can be simulated by numerical codes, and that vortices generated by aircraft in ground effect may last longer than previously thought. It is cautioned that additional research is needed before a credible wake vortex hazard can be estimated from these results.

Delisi, D. P., Robins, R. E. and Fraser, R. B.

"THE EFFECTS OF STRATIFICATION AND WIND SHEAR ON THE EVOLUTION OF AIRCRAFT WAKE VORTICES NEAR THE GROUND"

NWRA-87-R006, April 1987, Northwest Research Associates, Bellevue, WA

We have performed a feasibility study of how stratification and shear affect the evolution of aircraft trailing-tip vortices as they approach the ground and how they evolve when they are generated near the ground. The study incorporates both laboratory experiments and concurrent numerical modeling, matching model Froude numbers and shear parameters with their full-scale values. Our results indicate that stratification and shear can have significant effects on the evolution of the vortex system. In non-stratified, non-sheared flow, vortex evolution is symmetric, each vortex decaying at the same rate. Adding stratification maintains the symmetry but inhibits the vertical migration. In ground effect, stratification also inhibits horizontal migration and cancels the rebound effect (observed in the non-stratified, non-sheared case). In a non-stratified flow with shear, vortex evolution is asymmetric, and, in ground effect, the shear also acts to severely reduce the rebound effect. With stratification and shear (Richardson number equal to one), the flow is asymmetric, and two effects are observed. When the vortex pair is weak relative to the shear (strong crosswind condition), the weaker downwind vortex is closer to the ground than the stronger upwind vortex. (If the vortex pair is far from the ground, a solitary vortex develops in this case.) If the vortex is stronger relative to the shear (weak crosswind conditions), the weaker downwind vortex is further from the ground than the stronger upwind vortex. In either case, the vortices may migrate far from their initial generation position.

Delisi, D. P., Robins, R. E. and Lucas, R. D.

"INITIAL LABORATORY OBSERVATIONS OF THE EVOLUTION OF A VORTEX PAIR IN A STRATIFIED SHEAR FLOW"

Phys. Fluids A, Vol. 3, No. 11, November 1991, pp. 2489 - 2491

First results are presented for a laboratory experiment and a supporting numerical simulation of the evolution of a vortex pair in a stratified and sheared flow where the Richardson number is 1.0 and the vortex Reynolds number is 14,400. Both the laboratory experiment and the numerical model show that the vortex pair evolves into a single vortex. It is believed that these are the first reported experimental measurements on the evolution of a vortex pair in a stratified shear flow.

Delisi, D. P., Robins, R. E. and Pruis, M. J.

"APA3.8 FAST-TIME NUMERICAL WAKE MODEL DESCRIPTION AND FIRST RESULTS"

AIAA Paper 2016-3437, June 2016, Washington, DC.

Fast time, numerical wake vortex models are useful in examining a variety of problems, including determining an understanding of new procedures and exploring the evolution of aircraft wake vortices under a range of atmospheric conditions. Version 1 of the APA (AVOSS Wake Vortex Prediction Algorithm) fast time model was first completed in December, 1997. Since that version, development has continued, under funding from NASA. Version 3.8 is the latest version in this development, and includes (i) more realistic stratification effects, based on the use of laboratory experiments to describe entrainment and detrainment, (ii) better modeling of countersign vorticity, and (iii) more realistic vortex bouncing in crosswind flows.

Delisi, D. P., Robins, R. E., Switzer, G. F., Lai, D. Y. and Wang, F. Y.

"COMPARISON OF NUMERICAL MODEL SIMULATIONS AND SFO WAKE VORTEX WINDLINE MEASUREMENTS"

AIAA Paper No. 2003-3810, Orlando, FL, June 2003

To provide quantitative support for the Simultaneous Offset Instrument Approach (SOIA) procedure, an extensive data collection effort was undertaken at San Francisco International Airport by the Federal Aviation Administration (FAA, U.S. Department of Transportation). During the time period from March 2000 to October 2002, wake vortex data was measured for over 260,000 landing aircraft. The data set includes wake vortex measurements from Small, Large, and Heavy category aircraft. The measurements consist of cross-runway wind speed recorded every two seconds from three windlines, comprised of a series of propeller anemometers on three-foot poles near the threshold of runways 28L and 28R. The resulting data set is being used to demonstrate the feasibility of SOIA and to guide the improvement of the wake vortex model in the FAA airspace simulation tool ASAT (Airspace Simulation and Analysis for TERPS). We show that a slightly modified version of the AVOSS (Aircraft VORtex Spacing System) Prediction Algorithm (APA) produces lateral position predictions that agree well with the windline data. We also show that the data and the APA results agree with results produced by TASS (Terminal Area Simulation System), a numerical code developed by NASA. These comparisons between code and data provide an independent validation of the lateral transport estimates using windline sensors and give us increased confidence in both the data obtained from the windline sensors and our ability to predict vortex evolution using numerical simulations.

Delisle, M. R. and Takahashi, T. T.

"SPEED STABILITY AND OBSTACLE CLEARANCE DURING ENGINE INOPERATIVE TAKEOFF"

AIAA Paper 2018-3502, June 2018, Atlanta, GA.

This second paper in a series describes the consequences of unstable dynamic climb maneuvers performed during takeoff with a critical engine inoperative. If a pilot inadvertently commands horizon attitudes commonly experienced during normal all-engines-operating takeoff, the aircraft with a failed engine may not settle in to a stable climb. Instead, it will climb while losing speed. The rate at which speed is lost is a function of flight weight and the magnitude of mis-trim. For an aircraft resembling an A320 operated at 160,000-lbm, an aircraft may lose airspeed at a rate more than 2 knots per second if flown to customary horizon attitude. Once the pilot corrects this error and stabilizes climb, the aircraft will be flying under its scheduled speed. The consequences of flying under the scheduled speed can lead to a significant decrease in climb gradient. This impacts obstacle clearance capability and results in longer third segment acceleration phases. If aircraft are flown far enough below their scheduled speed, the associated terrain hazard consequences may be dangerous.

Denery, D. G., White, K. C. and Drinkwater, III, F. J.

"STATUS AND BENEFITS OF INSTRUMENTED TWO-SEGMENT APPROACHES; AUGUST, 1974"

Journal of Aircraft, Vol. 12, No. 10, October 1975, pp. 791-79.

NASA, in cooperation with the FAA, is evaluating the two-segment approach as a routine procedure for reducing aircraft noise. The program calls for separate flight evaluations using a 727 and a DC-8, and an extrapolation of these results to determine the adaptability of the technique to the rest of the fleet. The total program will be reviewed. The profile and procedures developed and the noise reduction achievable will be presented. The vortex characteristics behind an aircraft on a two-segment path will be covered. Finally, cost estimates for retrofitting aircraft with two-segment avionics will be presented.

Dengler, K.

"THE CREDOS REPORT: WP2 FINAL REPORT"

D2-6, October 2009.

This document summarizes and evaluates the results obtained from Work Package (WP) 2.

Dengler, K.

"EDDF-1 DATA COLLECTION CAMPAIGN REPORT"

CREDOS Report D2-1, February 2008, DLR, Munich, Germany.

This document describes the analysis of the EDDF-1 data set. It provides a detailed analysis of the meteorological situation and the wake vortex behavior gathered during the measurement campaign EDDF-1. In particular, a statistical analysis of the meteorological conditions is made, the crosswind conditions in combination with LIDAR measurements of wake vortices are analyzed, and finally a simple concept is proposed that could be useful to operations.

Dengler, K., Holzaepfel, F., Gerz, T., Wiegele, A., De Visscher, I., Winckelmans, G., Bricteux, L., Fisher, H. and Konopka, J.

"CROSSWIND THRESHOLDS SUPPORTING WAKE-VORTEX-FREE CORRIDORS FOR DEPARTING AIRCRAFT"

Meteorological Applications, Vol. 19, 2012, pp. 289-301

During two field measurement campaigns aircraft wake vortex trajectory and wind measurement data have been collected at Frankfurt airport. Three different approaches have been used to analyze the data to estimate crosswind threshold values supporting vortex-free corridors for departing aircraft. Although several competing effects such as wake vortex transport in and out of ground effect, temporal and spatial wind variability, and the spreading of aircraft trajectories after take-off, complicate the analyses, all three approaches lead to similar crosswind thresholds. Employing standard instrumentation at 10 m, a minimum crosswind threshold of 3.5-4.6 m/s has been identified to clear a safety corridor of 150 m width from wake vortices with a 95 percent probability within 60 s. Alternative estimations of crosswind thresholds employing different instrumentation and different height ranges are reported. Crosswind thresholds can be reduced if the wind is measured close to the air mass in which the vortices evolve. A definite crosswind threshold for operational use cannot be deduced solely from this study since critical factors such as risk and safety assessment have not yet been taken into account.

Denier, J. P. and Stott, J. A. K.

"THE DOMINANT WAVE MODE WITHIN A TRAILING LINE VORTEX"

Physics of Fluids, Vol. 17, 2005, pp. 014101-1 - 014101-9

We identify the dominant, or most unstable, wave mode for the flow in a trailing line vortex. This dominant mode is found to reside in a wavenumber regime between that of inviscid wave modes and the viscous upper branch neutral wave modes. A reevaluation of the growth rate in the vicinity of the upper branch of the curve of neutral stability allows us to predict the neutral value of the azimuthal and axial wavenumber as a function of the imposed swirl within the trailing line vortex.

Depommier, G., Labbe, O. and Sagant, P.

"EVOLUTION ANALYSIS OF THE MAIN MECHANISM OF THE JET/VORTEX INTERACTION"

International Journal for Numerical Methods in Fluids, Vol. 67, 2011, pp. 1024-1046.

A new analysis method of the jet/vortex interaction is presented to better understand the effect of each vortical structure on the others composing the jet and even on itself. Vortical structures are isolated from each other and the velocity field they produce is calculated by means of the Biot-Savart law. The structure influence on each another is then distinguished from the others by using its velocity field in the calculation of the vorticity momentum equations. Based on 3D-datafields provided by a large-eddy-simulation (LES) of the interaction between a Lamb-Oseen vortex and a turbulent round jet, a post-processing tool reduces the vortical structures and quantifies the different vorticity momentum equations terms. The study has been limited to the first steps of the interaction regime when there are still few vortical structures so that the subsequent analysis of the post-process results remains simple enough to be performed. The present method confirmed the intensification of azimuthal structures as they roll up around the main vortex. Core disturbance of the latter was found to be initially caused by those structures and not by core dynamic instabilities, which become dominant with the appearance of non-linear mechanisms.

Depommier, G., Labbe, O. and Sagaut, P.

"EVOLUTION ANALYSIS OF THE MAIN MECHANISMS OF THE JET/VORTEX INTERACTION"

AIAA Paper No. 2009-3707, June 2009, San Antonio, Texas.

A new analysis method of the jet/vortex interaction is presented to better understand the effect of each vortical structure on the others composing the jet and even on itself. Vortical structures are isolated from each other and the velocity field they produce is calculated by means of the Biot and Savart law. The structure influence on one another is then distinguished from the others by using its velocity field in the calculation of the vorticity momentum equations. Based on 3D-datafields provided by a Large-Eddy-Simulation of the interaction between a Lamb-Oseen vortex and a turbulent round jet, a post-processing tool reduces the vortical structures and quantifies the different vorticity momentum equations terms. The study has been limited to the first steps of the interaction regime when there is still few vortical structures so that the subsequent analysis of the post-process results remains simple enough to be performed. The present method confirmed the intensification of azimuthal structures as they roll-up around the main vortex. Core perturbation of the latter was found to be initially caused by those structures and not by core dynamic instabilities, which become dominant with the apparition of non-linear mechanisms.

Deptula, D. A.

"NASA/FRC WAKE TURBULENCE FLIGHT TEST PROGRAM: RIDE QUALITY ASPECTS"

NASA CR-145700, November 1975, Univ. of Virginia, Charlottesville, VA

To determine how much the ride quality of the Shuttle Carrier (Boeing 747) Aircraft is affected at various spoiler settings, the PEMS II (Portable Environmental Measuring System) was used to measure onboard motion during a test flight October 15, 1975. The PEMS II measures acceleration in the

vertical, transverse and longitudinal directions as well as angular rates of pitch, roll, and yaw. The data acquired by this instrument, combined with an airline passenger comfort model, gives an indication of how passengers would react to the motion induced by flying in a vortex alleviation configuration.

Desabrais, K. J. and Johari, H.

"DIRECT CIRCULATION MEASUREMENT OF A TIP VORTEX"

AIAA Journal, Vol. 38, No. 11, November 2000, pp. 2189-2191

The circulation of tip vortices has traditionally been calculated by performing integration over velocity or vorticity field. However, if vortex circulation is the primary parameter of interest, the direct measurement of circulation can be achieved via acoustic means, thus eliminating the need for detailed velocity measurements. The utilization of an ultrasonic technique is described, and the measured circulation values for a wing tip vortex are compared to those obtained with Particle Image Velocimetry. The authors concluded that the ultrasound method offers accurate circulation measurements as long as the flow scales are larger than the size of the sound pulse employed in the measurements.

Desabrais, K. J. and Johari, H.

"DIRECT CIRCULATION MEASUREMENT OF A WING TIP VORTEX USING ULTRASOUND"

AIAA Paper No. 1998-0609, Reno, NV, January 1998

The circulation distribution of a wing tip vortex as a function of the spanwise coordinate was measured directly by a novel ultrasound technique. This technique measures the total circulation enclosed by a rectangular path. To observe the effects of forcing on the vortex structure, blowing along the vortex core was employed. The wing tip vortex was generated by a blunt-ended, rectangular planform NACA 0012 wing with a chord of 10.5 cm and a half-wing aspect ratio of 2.1. The circulation distribution was measured at four chords downstream of the trailing edge of the wing. The circulation distribution behaved as expected achieving its highest level when the closed integration path surrounded the vortex. The circulation decreased rapidly through the vortex center before reaching nearly zero circulation outside the vortex. The ultrasound measurements agreed well with detailed circulation measurements derived from velocity field data generated by a similar tip vortex. The vortex was forced by both steady and pulsed injection and extraction of air into the core of the tip vortex. For blowing coefficients of 7.10×10^{-6} to 1.16×10^{-4} and a pulsing frequency range of 1-10 Hz, no appreciable changes were measured by the ultrasound method over the baseline flow at the four-chord station.

DeSantis, G. C. and Goodrick, T. F.

"WAKE SURVEY OF POWERED AND UNPOWERED C-5A AIRCRAFT MODELS"

AIAA Paper No. 1968-0931, El Centro, CA, 1968

As part of the development program to airdrop 50,000-pound unit loads from the C-5A aircraft, a wind tunnel study was initiated to investigate the flow characteristics in the wake of the aircraft during airdrop. Two models of the C-5A were used in the study, a 1/2 scale unpowered model and a 1/17 scale powered model. By using both the powered and unpowered models it was possible to completely determine the C-5A wake characteristics and to isolate the variations in the wake which were caused by the interaction of the engine discharge and the aircraft wake.

Deshpande, M. D.

"DECAY OF A THREE-DIMENSIONAL VORTEX IN AN ENCLOSURE"

Proceedings Royal Society of London, Series A, Vol. 457, No. 2011, July 2001, pp. 1533-1554.

Consider viscous, incompressible flow in a cubic container, generated by the uniform, linear motion of the top wall. Depending on the Reynolds number Re the flow could be laminar, transitional, or turbulent. If the motion of the top wall is now suddenly stopped, the fluid motion will begin to decay. Direct numerical simulations show that no matter what the initial conditions are, the final stages of decay follow an exponential law. To explain this interesting behavior of three-dimensional vortex motion, exact decaying, axisymmetric solutions of the Navier-Stokes equations were sought. It is shown that the field represents a swirling decaying vortex. These new exact solutions to the Navier-Stokes equations are used to identify and quantify the different regimes of vortex decay and scaling in the cubic cavity.

DeSouza, F. and Faghani, D.

"NEAR-FIELD WING TIP VORTEX MEASUREMENTS VIA PIV"

AIAA Paper No. 2001-2451, Anaheim, CA, June 2001

The paper presents some near-field properties of tip vortices generated by a rectangular NACA-0012 half-wing. Different end-cap geometries (flat, round, and elliptical), Reynolds numbers (0.5, 1.2 and 2×10^5 based on the chord) and angles of attack ($\alpha = 5$ degrees and 10 degrees) were considered in a low-speed wind tunnel. Measurements were performed by Particle Image Velocimetry (PIV) over a cross-flow plane at 2 chord lengths downstream of the trailing edge. Reynolds dependence of vortex properties such as vorticity or core size are investigated. Vortex wandering and its influence on high turbulence levels in the core region are analyzed. Finally, a Bi-Orthogonal Decomposition (Bi-POD) analysis of velocity fields is put forward. A Bi-POD-based entropy is defined in order to quantify the complexity of the vortex flow in each configuration.

DeSpirito, J.

"CFD VALIDATION OF INTERACTION OF FIN TRAILING VORTEX WITH DOWNSTREAM CONTROL SURFACE IN HIGH SUBSONIC FLOW"

AIAA Paper 2016-1546, January 2016, San Diego, CA.

Numerical simulations of the interaction of a fin trailing vortex with a downstream fin were performed to validate the numerical tools being used to characterize precision-guided munitions involving these type of vortex interactions. The predictions were validated against an existing experimental dataset involving the particle image velocimetry measurements of the mean and fluctuating velocities in the wake of a fin located on the wind tunnel floor. A grid resolution study concentrating on the mesh density in the wake region of the fin determined the adequate resolution: a minimum of 15-20 cells to define the vortex core. The predicted vortex characteristics compared reasonably well to the experimental data but had an initially higher intensity that was found to diffuse faster than the experimentally measured vortex. The predicted vortex trajectory was found to track closely to the experimental vortex trajectory. The predicted normal force coefficient on the downstream fin in the absence of interference from an upstream vortex agreed very well with the experimental data with a 3.1 percent difference at angle of attack of 10 degrees. The predicted bending moment slope was higher than the experimental, with a 15-degree difference in bending moment at angle of attack of 10 degrees. The predicted hinge (pitching) moment slope was much steeper than the experimental data, with a 100 percent difference in hinge moment at angle of attack of 10 degrees. However, the difference between the predicted and experimental center of pressure was 1.9 mm, only a 2.5 percent difference based on the fin root chord. The predicted aerodynamic coefficients on the downstream fin in the presence of vortex interference showed similar levels of agreement, with some exaggeration of the differences at the larger forward fin deflections.

deVelder, N. B.

"FREE WAKE POTENTIAL FLOW VORTEX WIND TURBINE MODELING: ADVANCES IN PARALLEL PROCESSING AND INTEGRATION OF GROUND EFFECTS"

MS Thesis, February 2014, University of Massachusetts, Amherst, MA.

Potential flow simulations are a great engineering type, middle-ground approach to modeling complex aerodynamic systems, but quickly become computationally unwieldy for large domains. An N-body problem with N-squared interactions to calculate, this free wake vortex model of a wind turbine is well suited to parallel computation. This thesis discusses general trends in wind turbine modeling, a potential flow model of the rotor of the NREL 5MW reference turbine, various forms of parallel computing, current GPU hardware, and the application of ground effects to the model. For approximately 200,000 points, current GPU hardware was found to be nearly 17 times faster than an OpenMP 12 core CPU parallel code, and over 280 times faster than serial MATLAB code. Convergence of the solution is found to be dependent on the direction in which the grid is refined. The 'no entry' condition at the ground plane is found to have a measurable but small impact on the model outputs with a periodicity driven by the blade proximity to the ground plane. The effect of the ground panel method was found to converge to that of the 'method of images' for increasing ground extent and number of panels.

Devenport, W. J. and Sharma, G.

"FAR-FIELD TURBULENCE STRUCTURE OF THE TIP VORTEX SHED BY A SINGLE RECTANGULAR WING"

Proceedings of the ASME 8th Symposium on Turbulent Shear Flows, Munich, September 9-11, 1991

The tip vortex shed by a single rectangular NACA 0012 wing is being studied. Helium bubble flow visualizations and extensive hot-wire velocity measurements have been performed over a wide range of conditions with the intent of revealing the far-field turbulence structure of this flow. At all conditions the vortex appears insensitive to probe interference and relatively stable. Some very low frequency ($f_c/U_{ref}=0.005$) lateral motions are present but these have an amplitude of less than $\pm 5\%$ of the wing chord. These motions dominate turbulence measurements made close to the vortex center. Away from the center the effect of the motions are much smaller, however, and the true turbulence structure is visible. This is dominated by the wing wake which forms a spiral around the core.

Devenport, W. J., Muthanna, C., Ma, R. and Glegg, S. A.

"TWO-POINT DESCRIPTIONS OF WAKE TURBULENCE WITH APPLICATION TO NOISE PREDICTION"

AIAA Journal, Vol. 39, No. 12, December 2001, pp. 2302-2307

Measurements of the four-dimensional two-point correlation tensor of a fully developed airfoil wake are presented. These data allow examination of the characteristic eddies of the turbulence through proper orthogonal decomposition and linear stochastic estimation. A simple generic technique has been developed to extrapolate the correlation tensor function from the Reynolds stress field based on the hypothesis that its form is largely determined by the constraints imposed by inhomogeneity and continuity. Estimates for the plane wake compare favorably with measurements, and, interestingly, proper orthogonal modes and characteristic eddy structures inferred from the estimates are like those obtained from measurements. This implies that these measures of the correlation function are largely determined by basic physical information, suggesting some simplification of the turbulence-modeling problem for applications such as aeroacoustics.

Devenport, W. J., Rife, M. C., Liapis, S. I. and Follin, G. J.

"TURBULENCE STRUCTURE AND SCALING IN TRAILING VORTICES, "

AIAA Paper No. 1995-0588, Reno, NV, 1995.

Experiments have been performed on the tip vortex trailing from a rectangular NACA 0012 half wing. Preliminary studies showed the vortex to be insensitive to the introduction of a probe and subject only to small wandering motions. Meaningful velocity measurements could therefore be made using hot-wire probes. Detailed analysis of the effects of wandering was performed to properly reveal the flow structure in the core region and to give confidence in measurements made outside the core. A theory has been developed to correct mean-velocity profiles for the effects of wandering and to provide complete quantitative estimates of its amplitude and contributions to Reynolds stress fields. Spectral

decomposition was found to be the most effective method of separating these contributions from velocity fluctuations due to turbulence. Outside the core the flow structure is dominated by the remainder of the wing wake which winds into an ever-increasing spiral. There is no large region of axisymmetric turbulence surrounding the core. Turbulence stress levels vary along the wake spiral in response to the varying rates of strain imposed by the vortex. Despite this complexity, the shape of the wake spiral and its turbulent structure reach an approximately self-similar form. Moving from the spiral wake to the core the overall level of velocity fluctuations greatly increases, but none of this increase is directly produced by turbulence. Velocity spectra measured at the core center scale in a manner that implies that the core generates no turbulence of its own. The core therefore appears to be laminar and velocity fluctuations here a consequence of inactive motion of the core as it is buffeted by turbulence of the surrounding wake. Mean velocity profiles through the core show evidence of a two-layered structure - an outer core possibly formed by roll up at the wing tip and an inner core that grows with distance downstream.

Devenport, W. J., Rife, M. C., Liapis, S. I. and Follin, G. J.

"THE STRUCTURE AND DEVELOPMENT OF A WING-TIP VORTEX"

J. Fluid Mech., Vol. 312, April 1996, pp. 67-106

Experiments have been performed on the tip vortex trailing from a rectangular NACA 0012 half-wing. Preliminary studies showed the vortex to be insensitive to the introduction of a probe and subject only to small wandering motions. Meaningful velocity measurements could therefore be made using hot-wire probes. Detailed analysis of the effects of wandering was performed to properly reveal the flow structure in the core region and to give confidence in measurements made outside the core. Outside the core the flow structure is dominated by the remainder of the wing wake which winds into an ever-increasing spiral. There is no large region of axisymmetric turbulence surrounding the core and little sign of turbulence generated by the rotational motion of the vortex. Velocity spectra measured at the vortex center scale in a manner that implies that the core is laminar and that velocity fluctuations here are a consequence of inactive motion produced as the core is buffeted by turbulence in the surrounding spiral wake.

Devenport, W. J., Rife, M. C., Liapis, S. I. and Miranda, J.

"TURBULENT TRAILING VORTICES"

AIAA Paper No. 1994-0404, Reno, NV, January 1994

Measurements were performed on the vortex shed from a rectangular NACA 0012 half wing over a range of conditions. These show the wing wake to dominate the turbulence structure both outside and inside the core. Peak turbulence levels in the wake decrease as the core is approached. Velocity spectra show the drop continuing into the core. Core-center spectra collapse well when they are scaled on wake velocity deficit and core radius but show no correlation when scaled using core parameters. It therefore appears that turbulence in the core is provided from the wake and that rates of strain

associated with the vortex core produce little if any turbulence of their own. A theory on the effects of vortex wandering on measurements is presented. The theory provides corrections for measured core parameters. It also shows that if sufficient wandering is present, the measurement of a q-vortex tangential velocity profile and a Gaussian axial velocity profile in the core is inevitable, regardless of the true flow field. A core similarity theory is also developed. This shows the growth of a vortex core to depend strongly on which parameters scale turbulence stresses at the core center. If they scale on peak tangential velocity, core growth rate rapidly becomes independent of Reynolds Number. If they scale on the wake velocity deficit (as evidenced by present measurements), growth rate is always a function of Reynolds Number, in qualitative agreement with established observations.

Devenport, W. J., Vogel, C. M. and Zsoldos, J. S.

"FLOW STRUCTURE PRODUCED BY THE INTERACTION AND MERGER OF A PAIR OF CO-ROTATING WING-TIP VORTICES"

J. Fluid Mech., Vol. 394, September 1999, pp. 357-377

Experiments have been performed to study the co-rotating wing-tip vortex pair produced by a pair of rectangular wings in a split-wing configuration. Detailed measurements made in cross-sections upstream and downstream of merger reveal, for the first time, the complex turbulence structure of this flow. The vortices spiral around each other and merge some 20 chord lengths downstream of the wings. As merger is approached the vortices lose their axisymmetry - their cores develop lopsided tangential velocity fields and the mean vorticity field is convected into filaments. The cores also become part of a single turbulence structure dominated by a braid of high turbulence levels that links them together. The braid, which quite closely resembles the structure formed between adjacent spanwise eddies of transitional mixing layers, grows in intensity with downstream distance and extends into the vortex cores. Unlike a single tip vortex, the unmerged cores appear turbulent. The merging of the vortices wraps the cores and the flow structure that surrounds them into a large turbulent region with an intricate double spiral structure. This structure then relaxes to a closely axisymmetric state. The merged core appears stable and develops a structure similar to the laminar core of a vortex shed from a single wing. However, the turbulent region formed around the vortex core during the merger process is much larger and more axisymmetric than that found around a single wing-tip vortex.

Devenport, W. J., Wenger, C. W., Glegg, S. A. L. and Miranda, J. A.

"WAVE NUMBER FREQUENCY SPECTRA OF A LIFTING WAKE FOR BROADBAND NOISE PREDICTION"

AIAA Journal, Vol. 36, No. 6, June 1998, pp. 881-887

Measurements of wave number frequency spectra of velocity fluctuations have been made using two three-component hot-wire probes in the wake of a rectangular NACA 0012 half-wing at a 5-deg angle of attack. Spectra were measured along spanwise lines in the near two-dimensional part of the wake, in the stretched region where the wake begins to wind around the vortex, directly above the vortex core, and radially from the core center. Dominated by the large-scale organized motions present in the wake,

the spectra show little similarity with the von Karman isotropic turbulence spectrum. Outside the core, upwash spectra contain a single maximum at the passage frequency of these large structures. Motions associated with this peak are highly anisotropic, both in terms of velocity components and length scales. Similar anisotropy is also seen at higher wave numbers, suggesting either that the smaller scale turbulent motions are organized by the large eddies or that the non-sinusoidal components of those eddies contribute significantly to the spectrum at higher wave numbers. The implications of these results for broadband noise prediction have been assessed by considering the sound radiation from this turbulent flow over a semi-infinite flat plate. The major conclusion is that the correlation length scales of the flow are small compared to the acoustic wavelength and so are well represented by their values at zero spanwise wave number. However, the blade response function has a variation with spanwise wave number that cannot be ignored and significantly influences the spanwise directionality.

Devenport, W. J., Zsoldos, J. S. and Vogel, C. M.

"THE STRUCTURE AND DEVELOPMENT OF A COUNTER-ROTATING WING-TIP VORTEX PAIR"

J. Fluid Mech., Vol. 332, February 1997, pp. 71-104

Experiments have been performed to examine the turbulence structure and development of a pair of counter-rotating wing-tip vortices. The vortices were generated by two rectangular NACA 0012 half wings placed tip to tip, separated by 0.25 chord lengths. Preliminary studies showed the vortices to be insensitive to the introduction of a probe and subject only to small wandering motions. Meaningful measurements could therefore be made using hot-wire probes. Three-component velocity measurements were made 10 and 30 chord lengths downstream of the wing leading edges for a chord Reynolds number of 260000. At 10 chord lengths the vortex cores are laminar. The turbulence that surrounds the cores is formed by the roll-up of and interaction of the wing wakes that spiral around them. This turbulence is stretched and organized but apparently not produced by the circulating mean velocity fields of the vortices. At 30 chord lengths the vortex cores have become turbulent. True turbulence levels within them are larger and increasing rapidly with radius. The turbulent region surrounding the cores has doubled in size and turbulence levels have not diminished, apparently being sustained by outward diffusion from the core regions. The distribution of the turbulence has also changed, the wake spirals having been replaced by a much more core-centered turbulence field. This change in flow structure contrasts sharply with what is seen in the equivalent isolated tip vortex, produced when one of the wings is removed. Here the vortex core remains laminar and the turbulence surrounding it decays rapidly with downstream distance. This implies that the transition to turbulence in the cores of the vortex pair is stimulated by interaction between the vortices. Spectral measurements at 10 chord lengths suggest that short-wave instability may be the cause.

Devenport, W., Zsoldos, J. and Vogel, C.

"TURBULENCE IN TRAILING VORTEX PAIRS"

20th Symposium, Naval Hydrodynamics, Santa Barbara, CA, August 1994, pp. 682-701

The turbulence structure associated with a pair of counter-rotating trailing vortices is examined through analysis of a large experimental database. The vortices were generated by two rectangular NACA 0012 half wings placed tip to tip, separated by 0.25 chord lengths. The database consists primarily of detailed 3-component hot-wire velocity records measured in planes 10 and 30 chord lengths downstream of the wing leading edges for a chord Reynolds number of 260,000. The data reveal much about the turbulence structure of the vortex cores, the surrounding spiral wakes, and their interaction. The wakes dominate turbulence structure outside the core regions. The drift of the vortex pair and the secondary flow they generate stretches and distorts the wakes, causes them to merge and separate again. While these events cause substantial changes in the organization and structure the wake-like character of the turbulence is never lost. The interaction between the vortex cores, in addition to producing Crow instability, appears to be a crucial player in their decay. Specifically, the interaction seems to stimulate turbulence production in the vicinity of the otherwise laminar cores, accelerating their growth. This previously unobserved mechanism provides a possible physical explanation of the two-stages of vortex decay seen in the far wakes of lifting vehicles.

DeVries, L. and Paley, D. A.

"WAKE SENSING AND ESTIMATION FOR CONTROL OF AUTONOMOUS AIRCRAFT IN FORMATION FLIGHT"

Journal of Guidance, Control, and Dynamics, Vol. 39, No. 1, January 2016, pp. 32-41.

The continued development of sophisticated aircraft with high-fidelity control systems will enable autonomous execution of challenging tasks such as aerial refueling and close-formation flight. To achieve such tasks autonomously, an aircraft must sense other aircraft in close proximity and position itself relative to them. For example, formation-flying aircraft must position themselves strategically to realize benefits of aerodynamic efficiency; aerial refueling requires the follower aircraft to intercept the filling nozzle attached to the leader aircraft. This paper uses lifting-line theory to represent a two-aircraft formation and presents a grid-based, recursive Bayesian filter for estimating the wake parameters of the lead aircraft using noisy pressure measurements distributed along the trailing aircraft's wing; the estimator also uses a binary, relative-altitude measurement to break the vertical symmetry. The paper employs measures of observability to quantify spatial regions prone to degraded estimation performance. Optimal control strategies are presented to steer the follower aircraft to a desired lateral position relative to the leader while simultaneously optimizing the observability of the leader's relative position. The control algorithms guide the follower aircraft along trajectories that maintain adequate observability, thereby guaranteeing estimator performance. Theoretical results are illustrated using numerical examples of a two-aircraft formation.

Deyst, Jr., J. J. and Serben, S.

"AUTOMATIC TRACKING OF WAKE VORTICES USING GROUND-WIND SENSOR DATA"

FAA-RD-77-11, January 1977, Charles Stark Draper Lab., Cambridge, MA

Algorithms for automatic tracking of wake vortices using ground-wind anemometer data are developed. Methods of bad-data suppression, track initiation, and track termination are included. An effective sensor-failure detection-and-identification system is also documented. System performance is verified using actual sensor data. Computer requirements for implementing the system in the field are summarized, and a plan for developing a general-purpose vortex-tracking simulation is presented.

Dezhe, Z. J. and Dubin, D. H. E.

"POINT VORTEX DYNAMICS WITHIN A BACKGROUND VORTICITY PATCH"

Physics of Fluids, Vol. 13, No. 3, March 2001, pp. 677-691

Recent experiments and simulations have observed that the interaction of strong vortices with a low vorticity background can strongly affect the dynamics of both vortices and background. This paper considers an idealized model of this interaction. The background is treated as a patch of uniform vorticity with a nearly circular shape. The strong vortices are treated as point vortices, and their total circulation is assumed to be small compared to that of the background. It is found that Kelvin waves on the boundary of the background patch can be driven to large amplitude by the strong vortices, eventually resulting in wave breaking and filamentation.

Dghim, M., Ferchichi, M. and Fellouah, H.

"STEREOSCOPIC PIV INVESTIGATION OF THE EFFECT OF SYNTHETIC JET ACTUATION ON A WING TIP VORTEX"

AIAA Paper 2017-3038, June 2017, Denver, CO.

The structure and development of a wing tip vortex under the effect of synthetic jet (SJ) actuation were experimentally investigated using high resolution Stereoscopic PIV technique. The SJ was pushed through two different nozzle geometries namely a straight SJ (SSJ) and a directed SJ (DSJ) mounted at the wing tip. Measurements at multiple locations downstream the trailing edge of the wing showed an increased core radius and a decreased circumferential velocity when the vortex was subjected to SJ actuation. The DSJ was found to outperform the SSJ by further stretching the vortex and promoting turbulent mixing at its core.

Dghim, M., Ferchichi, M. and Fellouah, H.

"MEANDERING OF A WING TIP VORTEX UNDER THE EFFECT OF SYNTHETIC JET ACTUATION"

AIAA Paper 2018-3372, June 2018, Atlanta, GA.

The meandering of a wing tip vortex under the effect of synthetic jet (SJ) actuation was experimentally investigated using high resolution Stereoscopic PIV technique. The SJ was injected through two different nozzle geometries, namely a straight SJ (SSJ) and a curved SJ (CSJ), mounted at the wing tip. Measurements at multiple locations in the wake indicated increased meandering

amplitudes when the vortex was subjected to SJ actuation. The increased meandering introduced additional turbulence within the vortex core. When corrected for meandering, high turbulence levels were contained within the periphery of the vortex core. This suggests that, despite the removal of the meandering-induced turbulence, the SJ actuation of both SSJ and CSJ cases promoted turbulent mixing within the periphery of the vortex core, with the effect being more pronounced for the CSJ case.

Dhanak, M. R.

"INTERACTION BETWEEN A VORTEX FILAMENT AND AN APPROACHING RIGID SPHERE"

Journal of Fluid Mechanics, Vol. 110, 1981, pp. 129-147.

The evolution of an infinitely long straight vortex filament in the presence of an approaching rigid sphere is considered. The fluid is regarded as being inviscid and incompressible. The shape of the vortex filament when the sphere is sufficiently far away from the vortex is determined approximately using linear theory. The subsequent evolution is followed numerically by integrating the nonlinear equation of motion.

Dhanak, M. R. and Marshall, M. P.

"VORTEX DESTABILIZATION BY A HARMONIC STRAIN FIELD"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 16-1 - 16-16

A mechanism for vortex destabilization is presented. The mechanism is based on the recognition that a pair of vortices, such as in the vortex trail of an aircraft or a vortex in ground effect, impose a weak strain-field upon each other causing the shape of the vortex core to distort from a circle. The presence of a pressure gradient can also induce a strain on a vortex. In general, the strain fields are unsteady and three-dimensional. For plane steady strain-fields, equations of fluid motion suggest that a Rankin-type vortex core of uniform vorticity and elliptical shape can exist in a state in which it (a) is steady and stationary, (b) rotates about its axis or nutates about a fixed axis, or (c) elongates indefinitely smearing the core into a thin layer. In state (a), for sufficiently weak strain fields, a vortex of small enough aspect ratio of the ellipse persists under such a plane strain, being robust to small disturbances present in the flow field. It is shown that if, however, a small periodically varying strain-field is superimposed on the basic field, then at certain frequencies and their harmonics, a resonance phenomenon takes place which destabilizes the apparently stable stationary vortex in finite time, causing it to flip into states (b) or (c), in which action of instabilities associated with higher, non-elliptical, mode of deformation of the vortex boundary by disturbances in the flow field leads to disintegration of the vortex structure. For a vortex of given strength, the frequencies and amplitude required for destabilization vary with the size of the basic strain-field. The potential of the phenomena for the vortex hazard problem is discussed.

Dhanak, M. R. and Vishwanathan, K. S.

"THE INTERACTION BETWEEN AN INJECTED VORTEX AND A ROLLING UP VORTEX SHEET"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 6-1 to 6-7

The interaction between two symmetrically located finite Rankine vortices and an elliptically loaded vortex sheet is examined in the Trefftz plane for a range of flow parameters. The Rankine vortices, which are placed over the sheet, have vorticity of opposite sign to that of the adjacent section of the vortex sheet. They may be considered to represent, in the Trefftz plane, vortices 'injected' into the flow from an upstream location. It is shown that there are in general three types of interactions which significantly affect the rolling up process. Accordingly, an interaction can result in straightforward merging, formation of subsidiary structures or considerable inboard displacement of the rolling up tip vortex. In the last case, the process should help to enhance the onset of the Crow instability considerably.

Di Pierro, B. and Abid, M.

"ENERGY SPECTRA IN A HELICAL VORTEX BREAKDOWN"

Physics of Fluids, Vol. 23, 2011, pp. 025104-1 - 025104-9.

Using spectrally accurate, direct numerical simulations, we show that vortices with axial flows (without an imposed strain) generate small scales, i.e., breakdown, when they are randomly perturbed. We show that the breakdown that occurs without the necessity of a stagnation point in the flow is nonlinear and that energy spectra of the breakdown present a range of a k to $-5/3$ power scaling (k being a wavenumber). These features are the same for centrifugally stable and unstable azimuthal velocities. However, centrifugally unstable azimuthal velocities promote mixing in vortices with an axial flow. We also find that vortex breakdown could be a physical mechanism against a finite time singularity in Navier-Stokes equations. Contrarily, we do not observe a breakdown using spectrally truncated Euler equations. For these equations we find a scaling of the energy spectra compatible with the existence of a finite time singularity.

Diana, T.

"AN EVALUATION OF THE IMPACT OF WAKE VORTEX RE-CATEGORIZATION: THE CASE OF CHARLOTTE DOUGLAS INTERNATIONAL AIRPORT"

Transportation Research Part A, Vol. 109, 2018, pp. 41-49.

This study compared departures before and after wake recat implementation at CLT. In both periods, departure counts and departure demand loaded highly onto Factor 1, arrival demand and gate departure delays onto Factor 2, and taxi-out time onto Factor 3. A two-level negative binomial mixed-effects model considered the random effects of approach conditions on operations. Only gate departure delay was significant within and across both samples. NextGen capabilities including wake recat appeared to minimize the random effects of instrument approach conditions (IAC) on operations

in both samples. Wake recat increased departure throughputs in IAC and enabled multiple departure pushes throughout the day.

Diaz, M. R. A., Yechout, T. R. and Bryant, E. M.

"THE RAKELET -- A WINGTIP MODIFICATION APPROACH TO IMPROVE ENDURANCE, RANGE AND FUEL SAVINGS"

AIAA Paper No. 2012-0669, January 2012, Nashville, TN.

Starting in 2008, the Air Force Research Laboratory and Air Mobility Command tasked the US Air Force Academy with examining the benefits of various wingtip devices using the KC-125 Stratotanker as a test bed. The investigation that this paper focuses on involved a new type of wingtip device which combines a winglet and a raked wingtip. This new device is called a Rakelet. An optimized Rakelet configuration was developed for the KC-135 by optimizing the size, cant angle, and toe out angle of the winglet component as well as the level of blending between the winglet and the raked wingtip components. Testing proved that the optimal configuration was 100 percent size, 15 degrees of cant and -2 degrees of toe, as well as 35 percent blending. An unblended but otherwise optimal configuration provided a best-case endurance and range potential improvement over the unmodified KC-135 wingtip of 9.85 percent and 7.51 percent respectively. A KC-135 mission analysis was performed, providing a rough estimate of \$34 million savings per year for the Air Force KC-135 fleet. Evaluation of Rakelet blending was accomplished using a second, larger scale model to improve resolution. The improvement potential of the 35 percent blended Rakelet over the unblended Rakelet was found to be an average 3.98 percent and 4.24 percent in endurance and range potentials respectively. Overall, the Rakelet concept was shown to provide a significant endurance, range and fuel savings potential over conventional wingtip, winglet and raked wingtip designs.

Diebold, J. M. and Bragg, M. B.

"WAKE-SURVEY TECHNIQUE FOR ICED SWEEP-WING AERODYNAMICS"

AIAA Journal, Vol. 53, No. 6, June 2015, pp. 1712-1715.

The value of the wake-survey technique for studying swept-wing icing is demonstrated. The drag decomposition demonstrated the physical mechanisms through which the ice altered the drag of the wing. The increase in profile drag from the separated flow field can be inferred from surface oil flow and force balance measurements, but the wake-survey method is able to quantify this change. More importantly, the wake survey can determine how an ice shape alters the performance of the wing along the span. For the particular ice shape and wing tested, the ice shape resulted in significant performance penalties over the outboard section of the wing. This information can be used to determine which sections along the span are most susceptible to ice.

Diebold, J. M. and Bragg, M. B.

"STUDY OF A SWEPT WING WITH LEADING-EDGE ICE USING A WAKE SURVEY TECHNIQUE"

AIAA Paper 2013-0245, January 2013, Grapevine, TX.

The aerodynamics of swept wings with leading-edge ice is very complex and not fully understood. Previous swept wing icing studies have only provided force balance measurements and/or qualitative flow visualization. To more fully understand the complex aerodynamics, it is necessary to understand how the ice influences the drag breakdown and the spanwise distributions of lift and drag. This paper utilizes 5-hole probe wake surveys and a far-field analysis to decompose the drag into profile and induced drag components and to determine the spanwise distributions of lift and drag. It is shown that the leading-edge ice primarily influences the profile drag and the induced drag is relatively unaltered. Features observed in the lift and drag distributions are related to features seen in the wake as well as in surface oil flow visualization.

Diederich, F. W.

"CHARTS AND TABLES FOR USE IN CALCULATIONS OF DOWNWASH OF WINGS OF ARBITRARY PLAN FORM"

NACA TN-2353, May 1951, Langley Aeronautical Laboratory, Langley Field, VA

Values of the downwash of a horseshoe vortex in incompressible flow are presented in the form of charts and tables. The use of the charts and tables in the calculations of the downwash of wings of arbitrary plan form is discussed. The results of a few calculations are compared with experimental results.

Dieterle, L., Ehrenfried, K., Stuff, R., Schneider, G., Coton, P., Monnier, J. C. and Lozier, J. F.

"QUANTITATIVE FLOW FIELD MEASUREMENTS IN A CATAPULT FACILITY USING PARTICLE IMAGE VELOCIMETRY"

18th International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF), June 1999

In order to investigate the long-term behavior of the wake vortex flow behind an aircraft, quantitative whole-field measurements have been carried out in a free flight analysis laboratory using the PIV (Particle Image Velocimetry) technique. Instantaneous velocity fields were measured in successive planes crosswise to the flight path of a free flying air-liner model, so that the evolution, interaction, and decay of vortices originating from the wing, flap and slat tips can be described. The optical measurement system consisting of two aerosol generators for seeding, a pulsed laser system for illumination, two CCD cameras for image recording and trigger electronics for synchronization had to be adapted to the test conditions of a catapult facility, where a long-lasting, unsteady 'single event' initiated by the model's launch is subject of the experimental study. The paper focuses on the technical aspects of interfacing a catapult facility and a digital PIV system.

Dieterle, L., Stuff, R., Vollmers, H. and Coton, P.

"WAKE VORTEX STUDIES IN THE ONERA CATAPULT FACILITY AND IN THE DNW WIND TUNNELS"

First ONERA-DLR Aerospace Symposium, June 1999, Paris, France.

As part of the European research programs WAVENC and EUROWAKE the wake vortex system behind (i) a free flying Airbus model and (ii) the DLR's ALVAST half model has been investigated experimentally in the ONERA catapult facility and in the DNW-LLF (large low-speed wind tunnel facility) respectively. Digital particle image velocimetry (PIV) was used for both testing campaigns. The two facilities offer different experimental access to the physical phenomena of vortex formation, evolution, and decay with one and the same measurement technique and require a particular adaptation of this measurement technique to the different test conditions each. In both cases tracer particles added to the flow were illuminated by a pulsed laser light sheet in a plane crosswise to the flight path of the model or to the main flow direction respectively. Two CCD cameras recorded neighboring areas of the flow field simultaneously. The PIV system operation was fitted to the facilities' requirements. Image data were evaluated utilizing the cross-correlation method. The resulting velocity and vorticity fields give quantitative information on the structure and motion of the trailing vortices in different frames of reference: a ground-based one for the catapult and a model's one for the wind tunnel.

Dietz, M., Kebler, M., Kramer, E. and Wagner, S.

"TIP VORTEX CONSERVATION ON A HELICOPTER MAIN ROTOR USING VORTEX-ADAPTED CHIMERA GRIDS"

AIAA Journal, Vol. 45, No. 8, August 2007, pp. 2062-2074

This paper presents a method to improve the tip vortex conservation in a computational fluid dynamics simulation of a helicopter main rotor. Our approach uses vortex-adapted Chimera child grids to achieve a local refinement of the grid in the vicinity of the vortex and thus reduce the numerical dissipation of the vortex. The method is applied to the higher-harmonic-control aero-acoustic rotor test case to evaluate its potential with respect to the prediction of blade-vortex interaction air-loads. To allow a meaningful comparison with the experimental data, the rotor is trimmed for thrust, as well as for longitudinal and lateral mast moments, using weak fluid-structure coupling with a flight mechanics code. We obtained a good overall agreement with the experimental data for both aerodynamics and blade dynamics. The effect of the improvement in tip vortex conservation is demonstrated by comparison with simulations without Chimera refinement and with the experimental results. It turned out that a very fine grid resolution in the vicinity of the vortex is necessary to capture the blade-vortex interaction air-loads. The required grid resolution was provided by a refinement of the vortex-adapted grids, allowing for a very good reproduction of the blade-vortex interaction air-loads, especially on the retreating blade side.

DiMarzio, C. A., Sonnenschein, C. M. and Jeffreys, H. B.

"AIRCRAFT WAKE VORTEX VELOCITY MEASUREMENTS USING A SCANNING CO₂ LASER DOPPLER VELOCIMETER"

Electro-Optics '75 International Laser Conf., Anaheim, CA, 1975, pp. 391-397

Aircraft wake vortex flow fields have been studied using a scanning laser Doppler velocimeter located adjacent to runway 31R at Kennedy International Airport in New York. Data has been obtained on vortex location, transport, and flow fields for a variety of aircraft. The data which has been analyzed was recorded with a one-dimensional laser Doppler system capable of measuring only the magnitude of a single velocity component. Although the optical range resolution determines the spatial resolution of the velocity profile in one direction, the laser system's excellent angular resolution makes it possible (assuming circular symmetry of the vortex) to obtain the tangential vortex velocity flow field. The resolution with which this function is obtained depends on the angular scan rate. With the present scan configurations, data points are obtained at approximately 1-degree intervals, corresponding to a resolution of 2 to 3 meters at ranges of 100 to 150 meters.

Dixit, H. N. and Govindarajan, R.

"VORTICES AND THE EFFECTS OF ATMOSPHERIC DENSITY STRATIFICATION"

Proceedings of the ICEAE, May 2009, Bangalore, India.

Our goal is to study the effects of atmospheric density stratification on the formation and longevity of aircraft trailing vortices. Towards this end, we study a series of model two-dimensional problems, two of which are presented here. The first is on the dynamics of a single vortex located at a density stratified layer. Due to the presence of the vortex, the density interface rolls up into a spiral. Centrifugal acceleration is shown to play a major role in reducing the life-span of the vortex. Due to the misalignment of the acceleration vector with the normal to the spiral interface, vorticity is created along the density interface, resulting in a spiral Kelvin-Helmholtz instability. At every interface where heavier fluid is closer to the vortex than lighter, the flow is also unstable due to a centrifugal Rayleigh-Taylor instability. In the second problem, centrifugal effects are neglected, i.e., the Boussinesq approximation is employed. Here gravity is shown to eat into the vortex and create small-scale structures, although the initial stratification is stable. In both cases, a turbulence-like state ensues. The relevance of the present work to aircraft trailing vortices is discussed in the introduction, and ongoing work addresses this problem more directly.

Dixit, H. N. and Govindarajan, R.

"STABILITY OF A VORTEX IN RADIAL DENSITY STRATIFICATION: ROLE OF WAVE INTERACTIONS"

Journal of Fluid Mechanics, Vol. 679, 2011, pp. 582-615.

We study the stability of a vortex in an axisymmetric density distribution. It is shown that a light-cored vortex can be unstable in spite of the 'stable stratification' of density. Using a model flow consisting of step jumps in vorticity and density, we show that a wave interaction mediated by shear is the

mechanism for the instability. The requirement is for the density gradient to be placed outside the vortex core but within the critical radius of the Kelvin mode. Conversely, a heavy-cored vortex, found in other studies to be unstable in the centrifugal Rayleigh-Taylor sense, is stabilized when the density jump is placed in this region. Asymptotic solutions at small Atwood number, At , show growth rates scaling as the cube root of At close to the critical radius, and the square root of At further away. By considering a family of vorticity and density profiles of progressively increasing smoothness, going from a step to a Gaussian, it is shown that sharp gradients are necessary for the instability of the light-cored vortex, consistent with recent work which found Gaussian profiles to be stable. For sharp gradients, it is argued that wave interaction can be supported due to the presence of quasi-modes. Probably for the first time, a quasi-mode which decays exponentially is shown to interact with a neutral wave to give exponential growth in the combined case. We finally study the nonlinear stages using viscous direct numerical simulations. The initial exponential instability of light-cored vortices is arrested due to a restoring centrifugal buoyancy force, leading to stable non-axisymmetric structures, such as a tripolar state for an azimuthal wavenumber of 2. The study is restricted to two dimensions, and neglects gravity.

Djojodihardjo, H.

"AIRCRAFT TRAILING VORTICES -- CIRRUS CLOUD INTERACTION AND GREEN AIRCRAFT TECHNOLOGY: AN OVERVIEW"

Proceedings of the 2013 IEEE International Conference on Space Science and Communication, July 2013, Melaka, Malaysia, pp. 318-323.

Anthropogenic solutions that can be offered by Aerospace Technology to address environmental changes known are known as green technology initiatives. Such initiatives, however, may only provide partial or temporary solutions, as learned from mankind experience through the ages. To this end, basic principles governing physical changes occurring in the earth's environment will be reviewed. In the efforts to intervene such process and thus maintaining the sustainability of the earth's environment, some scientific and technological guidelines to comprehend the natural phenomena and global changes are reviewed and discussed. In particular, efforts devoted to aircraft technology and aviation will be elaborated in view of the goal of maintaining the sustainability of the earth's environment. In addition to fuel burn, particular considerations are given to contrail and trailing vortices.

Djojodihardjo, H.

"REVIEW ON DEVELOPMENT AND RECENT PATENTS ON TRAILING VORTICES ALLEVIATION"

Recent Patents on Mechanical Engineering, Vol. 4, Issue 2, 2011, pp. 83-129.

Continuous research efforts have been devoted to the fundamental understanding of aircraft aerodynamics and the introduction of new concepts and innovations for the improvement of basic and fundamental aircraft aerodynamic performance, and hence economy, which leads to the enhancement

of lift and the reduction of drag. It is also well known that the trailing vortices which reflect the lift as well as drag characteristics of the aircraft could be optimized for better aircraft performance characteristics and reduction of environmental impact as well as hazardous interference to other flight vehicles and/or objects. Research in enhanced aerodynamic efficiency has led to geometrical modifications, novel devices and features on the aircraft wings, such as blended-wing-body configuration, airfoil profiles and winglet designs, introduction of and/or invention of sensors for identifying relevant physical phenomena or measuring devices, introduction of novel computational methods to assess the prevailing force system with better accuracy through meticulous modeling, and introduction of control system and procedures for wake vortices alleviation and aerodynamic configuration optimization. Typical winglets configuration can significantly reduce the induced drag (in the order of less than 10 percent) with a resulting increase in wing lift-drag ratio and near the design lift coefficient. The corresponding improvement in lift-drag ratio is more than twice as great as that achieved with the comparable wing-tip extension. As also observed in many aircrafts produced in the last decades, only winglets have demonstrated sufficient benefits to find application on modern airliners. Further enhanced aircraft aerodynamic performance are suggested by introduction of recent innovative designs and patents of winglets, sharklets, blended winglets, capped winglets, s-shaped winglets and spiroidal winglet. The review identifies stability of various configurations of vortices, vortex decay and means of reducing vortex hazard. Passive wake vortices alleviation systems utilize the natural evolution of the instability modes with the highest growth rates while active systems rely on accelerating selected modes of instability by imposing the vortices individually or as a system. The passive system is essentially a vortex wake, hence an aerodynamic surface design, while an active system is an actuator design effort, respectively.

Djojodihardjo, H.

"SIMULATION OF ROLLING MOMENT INDUCED BY VARIOUS AIRCRAFT TRAILING VORTICES VORTEX MODELS: REVIEW AND ANALYSIS"

Proceedings of 17th International Conference on Mathematical and Computational Methods in Science and Engineering, April 2015, Kuala Lumpur, Malaysia, pp, 224-233.

It is well known that the trailing vortices which reflect the lift as well as drag characteristics of the aircraft could be optimized for better aircraft performance characteristics and reduction of environmental impact as well as hazardous interference to other flight vehicles and/or objects. Attention is given to identify the stability of various configurations of vortices, vortex decay and means of reducing vortex hazard. Passive wake vortices alleviation systems utilize the natural evolution of the instability modes with the highest growth rates while active systems rely on accelerating selected modes of instability by imposing the vortices individually or as a system. The passive system is essentially a vortex wake, hence an aerodynamic surface design, while an active system is an actuator design effort, respectively. Within such frame of thought, various vortex Aircraft Trailing Vortices Vortex Models are reviewed and analyzed in view of their potentials Wake Hazard Alleviation, by simulating the rolling moment induced. The simulation of various vortex model chosen are judged by their expected characteristics that may reproduce actual state-of-affairs.

Doetter, F., Aumann, P., Acisu, I., Brodersen, O. and Ronzheimer, A.

"A400M WAKE FLOW STUDIES BASED ON RANS CFD METHODS ON HYBRID MESHES"

RTO-MP-AVT-133, Proceedings Fluid Dynamics of Personnel and Equipment Precision Delivery from Military Platforms, Paper 7, 2006, Neuilly-sur-Seine, France, pp. 7-1 - 7-12.

Knowledge of flow conditions in the vicinity of the aft section of military transport aircraft is crucial to ensure the safe and precise deployment of personnel and material. CFD methods used by Airbus and DLR allow valuable predictions of these conditions, considering the influence of flow deflectors, sponsons, open cargo hold doors/ramps, as well as propulsion slip-streams. With the requirement of precisely delivering personnel and/or equipment into an area of limited size, while guaranteeing safe conditions for the airframe (as well as paratroops/dropped equipment), military transport aircraft pose unique challenges to aerodynamics. Among them: Guaranteeing the safety of parachutists, whose near aircraft trajectory is significantly influenced by the aircraft wake shedding substantial vorticity; and providing safe operational conditions within the aircraft while open doors strongly influence the internal air flow.

Dogan, A., Blake, W. and Haag, C.

"BOW WAVE EFFECT IN AERIAL REFUELING: COMPUTATIONAL ANALYSIS AND MODELING"

Journal of Aircraft, Vol. 50, No. 6, November-December 2013, pp. 1856-1868.

Mechanisms contributing in the 'bow wave' effect of a receiver on a tanker are investigated, and a modeling method for dynamic simulation is developed. Vortex lattice and Cart3D codes are used to calculate the aerodynamic forces and moments for a C-141B behind a KC-135. The vortex lattice code significantly underpredicts the bow wave effect, whereas the Cart3D code shows good agreement with available flight data. The modeling method uses stream functions for inviscid flow around solid bodies. The flow field induced by the presence of aircraft bodies is superimposed on the flow field generated by horseshoe vortices. The resultant flow field is approximated by the effective uniform translational and rotational velocity components, which are used in the buildup equations for the aerodynamic force and moment coefficients of both tanker and receiver aircraft. This method applied to a flying wing behind a KC-135 shows good agreement with Cart3D results. It is concluded that the major contribution to the 'bow wave' effect is the effect of the displacement of air due to the volume of the receiver and not upwash from the bound vortex due to the lift of the receiver. This disagrees with earlier studies that did not have the benefit of flight data to use as a benchmark.

Dogan, A., Lewis, T. A. and Blake, W.

"FLIGHT DATA ANALYSIS AND SIMULATION OF WIND EFFECTS DURING AERIAL REFUELING"

J. Aircraft, Vol. 45, No. 6, November-December 2008, pp. 2036-2048

This paper presents the analysis of the data obtained in an automated aerial refueling test flight conducted with a KC-135 as the tanker and a Learjet 25 as the surrogate receiver unmanned aerial

vehicle. The purpose of the analysis is to identify the wind induced by the tanker wake and its effect on the receiver aircraft. From the available flight data, a direct computation of the winds experienced by the tanker and receiver is carried out. The mean variation of the receiver wind is compared with the tanker wind when the receiver is at the observation and contact positions. This results in the identification of the wake-induced wind. A spectrum analysis is conducted to characterize the turbulence and to identify the pilot effects. The paper also presents methods used to model 1) prevailing wind, 2) wake-vortex-induced wind, and 3) turbulence as the three sources of wind that the aircraft are exposed to and the approach used for incorporating the wind effect into the dynamic simulation of the aircraft. The test flight is simulated in various cases with different turbulence models and flight controllers. The simulation results are analyzed and compared with the flight data in terms of the power spectral densities and mean variations to validate the wind and turbulence modeling techniques.

Dogan, A., Lewis, T. A. and Blake, W.

"WAKE-VORTEX INDUCED WIND WITH TURBULENCE IN AERIAL REFUELING -- PART A: FLIGHT DATA ANALYSIS"

AIAA Paper 2008-6696, Honolulu, HI, August 2008.

This paper presents the analysis of the data obtained in an automated aerial refueling test flight conducted with a KC-135 as the tanker and a Learjet 25 as the surrogate receiver UAV. The purpose of the analysis is to identify the wind induced by the tanker wake and its effect on the receiver aircraft. From the available flight data, a direct computation of the winds experienced by the tanker and receiver is carried out. The mean variation of the receiver wind is compared with the tanker wind when the receiver is at the observation and contact positions. This results in the identification of the wake-induced wind. Further, a spectrum analysis is conducted to characterize the turbulence and to identify the pilot effects. This paper is the first of a series of two papers. In the second paper (Part B), the flight data analyzed herein are used to validate a modeling and simulation technique.

Dogan, A., Lewis, T. A. and Blake, W.

"WAKE-VORTEX INDUCED WIND WITH TURBULENCE IN AERIAL REFUELING -- PART B: MODEL AND SIMULATION VALIDATION"

AIAA Paper 2008-6697, Honolulu, HI, August 2008

This paper is the second of a series of two papers. The first paper (Part A) presents the analysis of the data obtained in an automated aerial refueling test flight conducted with a KC-135 as the tanker and a Learjet 25 as the receiver. The purpose of the analysis is to identify the turbulence and wind induced by the tanker wake and their effect on the receiver aircraft. This paper presents the methods used to model (i) prevailing wind, (ii) wake vortex induced wind and (iii) turbulence as the three sources of wind that the aircraft are exposed to and the approach used for incorporating the wind effect into the dynamic simulation of the aircraft. The test flight is simulated in various cases with different turbulence

models and flight controllers. The simulation results are analyzed and compared with the flight data in terms of the power spectral densities and mean variations in order to validate the wind and turbulence modeling techniques.

Dogan, A., Venkataramanan, S. and Blake, W.

"MODELING OF AERODYNAMIC COUPLING BETWEEN AIRCRAFT IN CLOSE PROXIMITY"

Journal of Aircraft, Vol. 42, No. 4, July-August 2005, pp. 941-955

A method is developed for modeling the aerodynamic coupling between aircraft flying in close proximity. Velocities induced on a trailing aircraft by vortices from an aircraft upstream are written as a function of the relative separation and relative orientation between the two aircraft. The nonuniform vortex-induced wind and wind gradients acting on the trail aircraft are approximated as effective uniform wind and wind gradients. In a dynamic simulation, the effective wind can be used directly in the equations of motion, whereas the wind gradient can be used in the standard buildup equations for the aerodynamic moments. This removes necessity to explicitly compute the induced forces and moments. Various vortex models for estimating induced velocities and averaging schemes for computing effective wind components and gradients are assessed. Results from the method are compared to wind-tunnel data for a formation of two similar aircraft. A good match is obtained between experimental data and the predicted incremental force and moment coefficients induced on the trail aircraft. It is briefly discussed how the effective wind components and gradients can be incorporated into equations of motion of aircraft flying in a vortex field.

Doggett, Jr., R. V., Rivera, Jr., J. A. and Stewart, E. C.

"FLUTTER CLEARANCE FLIGHT TESTS OF AN OV-10A AIRPLANE MODIFIED FOR WAKE VORTEX FLIGHT EXPERIMENTS"

NASA TM-109168, April 1995, NASA Langley Research Center, Hampton, VA

Envelope expansion, flight flutter tests of a modified OV-10A aircraft are described. For a wake vortex research program, the airplane was modified to incorporate three, forward-extending instrumentation booms, one extending forward from each wing tip and one from the right side of the fuselage. The booms are instrumented with sensors to measure the velocity and direction of local air flow. The flutter tests results show that the modified OV-10A aircraft is free from flutter at speeds up to 330 KEAS at 5000 feet altitude.

Doig, G., Barber, T. J. and Neely, A. J.

"AERODYNAMIC CHARACTERISTICS OF A SWEPT WING IN CLOSE GROUND PROXIMITY AT HIGH SUBSONIC MACH NUMBERS"

Journal of Aerospace Engineering, Vol. 25, No. 4, October 2012, pp. 600-612.

The potential positive influence of close ground proximity on the aerodynamic performance of a wing has long been established; however, flight at a Mach number that causes shock waves to form between the wing and the ground plane would have significant aerodynamic consequences. A numerical study to investigate the effects of extremely low-level flight at subsonic Mach numbers up to 0.9 was conducted involving the symmetric, swept ONERA M6 wing. The aerodynamic coefficients as well as the pressure distributions and tip vortex behavior were analyzed for cases involving the angle of incidence, ground clearance, and Mach number as variables. It was found that lift was augmented with decreasing ground clearance in most cases with the wing at positive incidence, although the critical Mach number for the wing, in particular for the lower surface, was reduced at very low clearances. The earlier emergence of a lower shock was accompanied by a considerable increase in drag, although this was offset in part by a marked decrease in the strength of the tip vortex when the wing was within one chord length of the ground plane. As a result of the more pronounced shock structures and separation regions that occur above a freestream Mach number of 0.8, there is no net aerodynamic efficiency to be gained from flight with this wing in close ground proximity compared with unbounded flight at altitude.

Dolfi-Bouteyre, A., Augere, B., Besson, C., Canat, G., Fleury, D., Gaudo, T., Goular, D., Lombard, L., Planchat, C., Valla, M., Cariou, J.-P., Petilon, O. and Lawson-Daku, J.

"1.5 MICRON ALL FIBER PULSED LIDAR FOR WAKE VORTEX MONITORING"

Conf. on Lasers and Electro-Optics, CLEO/QELS 2008, May 2008, pp. 1-2

A pulsed fiber lidar based on 1.5-micron fiber technology has been demonstrated for wake vortex monitoring on airport sites. The wake vortex cores position resolution is plus/minus 2 m, the error on circulation 10 percent.

Dolfi-Bouteyre, A., Augere, B., Bourdon, P., Canat, G., Cezard, N., Dobroc, A., Durecu, A., Fleury, D., Le Gouet, J., Goular, D., Lombard, L., Planchat, C., Renard, W., Valla, M. and Besson, C.

"NEW FIBER LASER AND COHERENT LIDAR DEVELOPMENTS AT ONERA"

17th Coherent Laser Radar Conference, June 2013, Barcelona, Spain.

Onera has been developing lidars for military, environmental, and aeronautical applications for more than 30 years. The main instrumental developments deal with wind/wake vortex lidar for airport and environmental applications, lidar vibrometer for identification purpose or seismology applications, dial and supercontinuum lidars for gas detection and identification, airborne lidar for navigation sensors. In parallel, the team has a strong involvement in fiber laser technology in order to develop laser sources suitable to lidar applications. The main objective are the power scaling of fiber laser sources to increase lidar range, measurements accuracy and/or measurement rate. This implies the development of new active fibers, new technologies to overcome the stimulated Brillouin threshold or architectures involving coherent combining of amplifiers. Other developments deal with new wavelengths narrow linewidth fiber lasers or supercontinuum lasers to address particular gas species detection. In this

paper, we focus on innovative fiber laser developments and their integration in lidar systems for wind or gas monitoring. We also present new developments for two lidar applications: lidar vibrometer for structural damage assessment, and supercontinuum lidar for remote spectroscopy. Two other topics (wake vortex detection and wind sensing using coherent combining), are presented in dedicated papers.

Dolfi-Bouteyre, A., Augere, B., Valla, M., Goular, D., Fleury, D., Canat, G., Planchat, C., Gaudo, T., Besson, C., Gilliot, A., Cariou, J.-P., Petilon, O., Lawson-Daku, J., Brousmiche, S., Lugan, S., Bricteux, L. and Macq, B.

"AIRCRAFT WAKE VORTEX STUDY AND CHARACTERIZATION WITH 1.5 MICRON FIBER DOPPLER LIDAR"

Onera AerospaceLab Journal, Issue 1, Dec. 2009, pp.1-12.

For 10 years now, Onera has been developing lidar tools for wake vortex detection and studies. Since 2003, new developments based on 1.5- micron fibered laser sources have been achieved in parallel with extensive research work on the laser sources themselves. Three innovative lidars have been developed and are presented in this paper: 1) A mini-lidar, based on a CW 2W/1.5-micron laser source, for aircraft model wake vortex characterization in a catapult facility. A self-triangulation technique allows the vortex core position to be found with 10 cm error, and the circulation error is 10 percent. 2) A pulsed 1.5-micron lidar, based on a 50 microjoule/15 kHz Master Power Oscillator Power Amplifier (MOPA) source, for lateral wake vortex monitoring at airports. The range is 400 m, the core position error is about +/- 2 m and the circulation error is about 10 percent. 3) A pulsed 1.5-micron lidar, based on a 120 microjoule/12 kHz MOPA source, for onboard axial wake vortex detection. Ground based lidar tests at Orly airport demonstrated wake vortex detection up to 1.2 km..

Dolfi-Bouteyre, A., Canat, G., Valla, M., Augere, B., Besson, C., Goular, D., Lombard, L., Cariou, J.-P., Durecu, A., Fleury, Bricteux, L., Brousmiche, S., Lugan, S. and Macq, B.

"PULSED 1.5-MICRON LIDAR FOR AXIAL AIRCRAFT WAKE VORTEX DETECTION BASED ON HIGH-BRIGHTNESS LARGE-CORE FIBER AMPLIFIER"

IEEE Journal of Selected Topics in Quantum Electronics, Vol. 15, No. 2, March/April 2009, pp. 441-450.

In this paper, we present the development of an axial aircraft wake vortex light detection and ranging (LIDAR) sensor, working in the Mie scattering range, based on pulsed 1.5-micron high-brightness large-core fiber amplifier. An end-to-end Doppler heterodyne LIDAR simulator is used for the LIDAR design. The simulation includes the observation geometry, the wake vortex velocity image, the scanning pattern, the LIDAR instrument, the wind turbulence outside the vortex, and the signal processing. An innovative high-brightness pulsed 1.5-micron laser source is described, based on a master oscillator power fiber amplifier (MOPFA) architecture with a large-core fiber. The obtained beam quality is excellent, and achieved pulsed energy is 120 micro-Joules with a pulse repetition frequency of 12 kHz and a pulse duration of 800 ns. A Doppler heterodyne LIDAR is developed based on this laser source with a high-isolation free-space circulator. The LIDAR includes a real-time display of the wind field.

Wind dispersion is postprocessed. Field tests carried out at Orly airport in April 2008 are reported. Axial aircraft wake vortex signatures have been successfully observed and acquired at a range of 1.2 km with axial resolution of 75 m for the first time with fiber laser source.

Dolfi-Bouteyre, A., Cariou, J.-P., Fleury, D., Goular, D. and Lafforgue, J. P.

"MEASUREMENT OF AIRCRAFT WAKE VORTEX USING COHERENT LASER RADAR: COMPARISON BETWEEN CATAPULT AND AIRPORT MEASUREMENTS"

13th Coherent Laser Radar Conf., October 2005, Kamakura, Japan.

Coherent laser radar or lidar is a powerful technique for detection and study of aircraft wake vortices. The technique measures the Doppler shift of light scattered from atmospheric particles, and hence infers the line-of-sight flow velocity allowing a picture of vortex flow to be built up. CW lidar technique has been used in reduced scale studies in catapult facilities and for full-scale aircraft wakes measurements and is the link between both approaches. In ONERA's B20 new catapult facility, non-motorized scaled models are accelerated by means of a pneumatic catapult via a trolley and then released as a free-flying model. Smoke generators on the ground are used to seed the vortices. Measurements are obtained at high spectral and angular resolution. Using a self-triangulation technique, the position of the cores and their trajectories over time is determined with 15 cm accuracy. This new measurement instrumentation will be presented in detail. During the AWIATOR program, ONERA 10-micron continuous wave lidar was coupled with a DLR 2-micron pulsed lidar. The pulsed lidar monitored the seeded vortices of a large transport aircraft (vortex position and circulation) while detailed measurements of velocity profiles were obtained with ONERA's continuous-wave lidar. The lidar appears to be an essential tool to check the scale factor between model and true aircraft and to analyze external factors such as wind and atmospheric turbulence on vortex decay. Comparison of catapult and field test measurements will be presented.

Dolfi-Bouteyre, A., Goular, D., Planchat, C., Loaec, S., Thobois, L., Cariou, J.-P., Barbaresco, F., Juge, P., Orlandi, F., Ricci, Y. and Klein, M.

"ALL-WEATHER SENSORS (LIDAR + RADAR) FOR WAKE-VORTEX HAZARDS MITIGATION ON AIRPORT"

17th Coherent Lidar Conference, June 2013, Barcelona, Spain.

RADAR and LIDAR sensors are complementary in terms of ambient weather conditions: X-band Radar performances are optimal under rainy conditions whereas Lidar performances are optimal in dry air. During SESAR XP0 and XP1 trials in CDG airport, a multi-function (wake-vortex, weather) electronic scanning X-band Radar (THALES), and a multifunction 1.5-micron Lidar with a 3D scanner (Leosphere with Onera signal processing) have been used together to detect and follow aircraft wake vortices. These sensors were associated in an all-weather conditions system. Trials configuration is presented and test results are analyzed.

Dolfi-Bouteyre, A., Valla, M., Augere, B., Cariou, J.-P., Goular, D., Fleury, D., Canat, G., Planchat, C., Gaudo, T., Lombard, L., Petilon, O. and Lawson-Daku, J.

"1.5 MICRON ALL FIBER PULSED LIDAR FOR WAKE VORTEX MONITORING"

14th Conference on Coherent Laser Radar, Snowmass, CO, July 2007

A new 1.5-micron pulsed lidar using an all-fiber laser source has been developed by ONERA in cooperation with Leosphere, for wake vortex and wind field measurements. This paper illustrates the good results obtained with a pulsed lidar based on MOPFA 1.5-micron laser, for detection and monitoring of wake vortices on airport fields. Operational ranges larger than 400m have been demonstrated with a 60 microjoule, 15kHz, 250ns pulse fiber doped Er laser. Wake profiles, positions and circulations can be derived from recorded data.

Doligalski, T. L., Smith, C. R. and Walker, J. D. A.

"VORTEX INTERACTIONS WITH WALLS"

Annual Review of Fluid Mechanics, Vol. 26, 1994, pp. 573-616

The response of a viscous boundary layer to vortex motion has been described in this article, with an emphasis on flows at high Reynolds number. In general, a boundary-layer eruption occurs in such circumstances in the form of a thin spire containing significant levels of vorticity, which usually rolls up into one or more secondary vortices. This regenerative process of vortex-induced separation is evidently a common phenomenon occurring in a wide variety of applications, some of which are described here. Because these eruptions develop and take place in moving reference frames and involve sharply focused eruptions that occur abruptly (at times and locations that are not easily predicted a priori), experimental and computational research on such phenomena is extremely challenging. It is evident that conventional experimental techniques, wherein measurements are taken at fixed points in space, are virtually useless in attempting to detect such phenomena. Progress can be made using combinations of innovative flow visualization and particle image velocimetry; however, a moving reference frame is often crucial to proper interpretation of vortex-induced events. It is also worth noting that a substantial increase in resolution may be required in current PIV methods in order to capture the abrupt narrow-band eruptions.

Domel, N. D., Charlton, E. F. and Miller, D. N.

"MINIMALLY INTRUSIVE WINGTIP VORTEX WAKE MITIGATION USING MICROVANE ARRAYS"

US Patent Application, 2013/0146715 A1, June 2013.

An airfoil tip vortex mitigation arrangement comprising one or more flow directors configured and positioned to re-direct freestream air over a low-pressure surface of an airfoil in such a way as to displace and weaken a main tip vortex generated at a tip of the airfoil.

Donaldson Jr., R. J.

"VORTEX SIGNATURE RECOGNITION BY A DOPPLER RADAR"

J. Applied Meteorology, Vol. 9, August 1970, pp. 661-670

A scanning Doppler radar has capability for measurement of the tangential shear of radial velocity or gradient of the radial component of velocity in a direction normal to the radial vector. Tangential shear of sufficient magnitude in a horizontal direction reveals one term of the expression for vorticity in a horizontal plane. A vortex is reasonably well identified by Doppler radar if the shear is sufficiently steady during the time required for half a revolution of a vortex, and is further confirmed by extension of the shear pattern throughout a depth greater than its diameter, and by invariance of the character of the shear with respect to a change in viewing angle. A vortex in solid rotation has a characteristically uniform signature on a Doppler velocity display which may, however, be smoothed down according to the resolution limitations of the antenna beam. Sharp velocity peaks are rounded down to roughly half the magnitude of the velocity interval encompassed within the half-power antenna beamwidth.

Donaldson, C. duP.

"A BRIEF REVIEW OF THE AIRCRAFT TRAILING VORTEX PROBLEM"

AFOSR-TR-71-1910, May 1971, Aeronautical Research Assoc. of Princeton, Princeton, NJ

In this paper, an attempt will be made to review the simplest theory of the wake, as well as to bring to attention a more detailed description of vortex roll-up that has been available for many years. This more complete description of the wake is in far better agreement with experimental results than the conventional description and may be used to illustrate several problems that face the experimentalist in the interpretation of this data. Once the roll-up problem has been discussed, the ways in which trailing vortex systems may be dissipated are reviewed. Finally, a system for evaluating the danger potential of aircraft wakes is discussed and the wake characteristics of a representative selection of present-day aircraft are presented in terms of this method of classifying aircraft wakes.

Donaldson, C. duP.

"CALCULATION OF TURBULENT SHEAR FLOWS FOR ATMOSPHERIC AND VORTEX MOTIONS"

AIAA Journal, Vol. 10, No. 1, January 1972, pp. 4-14

The basic ideas behind methods for computing the transport properties of turbulent shear flows for the past several decades are reviewed. Their shortcomings, insofar as computing several problems that arise in nature, are discussed. Particular emphasis is given to the case of vortex flows and atmospheric motion. The results of several years' effort toward establishing a general method for computing turbulent shear flows which does not suffer from the shortcomings of the older methods are reviewed, and a new method for the calculation of turbulent shear flows is suggested. The new results obtained when this method is applied to the computation of simple atmospheric motions and to vortex flows are presented and discussed in some detail.

Donaldson, C. duP.

"VORTICES AND AIRCRAFT PERFORMANCE"

Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, Air Force Flight Dynamics Laboratory, AFFDL-TM-75-16-FGC, 1974, pp. 11-17

A review is given on ARAP's work on the roll-up and initial organization of vorticity shed by the wing of an aircraft and on the aging effects in the far wake due to viscosity (molecular and turbulent). The modified Betz model was shown to be an effective approach to the roll-up problem; it includes the effect of distributed wing drag on vortex structure. In considering the far-field flow, a detailed second-order numerical closure model has been developed for the axisymmetric vortex under the usual assumptions of equilibrium between the production and convection of turbulent energy.

Donaldson, C. duP. and Bilanin, A. J.

"VORTEX WAKES OF CONVENTIONAL AIRCRAFT"

AGARDograph No. 204, May 1975, Aero. Research Assoc. of Princeton, Princeton, NJ

A review is made of the present state of our knowledge of the vortex wakes of conventional aircraft. Included are discussions of wake roll-up, geometry, instability, and turbulent aging. In the light of these discussions, a brief review is made of the persistence of vortices in the atmosphere and design techniques which might be used to minimize wake hazard are considered.

Donaldson, C. duP. and Sullivan, R. D.

"DECAY OF AN ISOLATED VORTEX"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 389-411

The effect of turbulent shear on the decay of a single vortex is considered. The ultimate aim of the program is the development of a method by which the effects of turbulence, whether introduced initially in the center of a vortex or contained in the fluid in which the vortex is formed, could be calculated.

Donaldson, C. duP., Bilanin, A. J. and Crow, S. C.

"VORTEX WAKES OF LARGE AIRCRAFT"

Notebook for AIAA Professional Study Seminar, June 1974, Aeronautical Research Assoc. of Princeton, Princeton, NJ

A compendium of lecture notes on the subject of vortex wakes of large aircraft. The notes include the following topics: rollup of shed vorticity, new roll-up models, comparison of rollup computations with experiments, interactive motion of shed vorticity, aging of vortices, vortex breakdown, mutually induced instabilities, atmospheric effects, and the impact on aircraft design.

Donaldson, C. duP., Snedeker, R. S. and Sullivan, R. D.

"A METHOD OF CALCULATING AIRCRAFT WAKE VELOCITY PROFILES AND COMPARISON WITH FULL-SCALE EXPERIMENTAL MEASUREMENTS"

AIAA Paper No. 1974-0039, Washington, DC, January 1974

A method is developed for the calculation of the initial inviscid form of rolled-up wake vortices behind a wing having arbitrary lift distribution. The method makes use of the Betz assumptions of conservation of wake vorticity and moments of vorticity. It is found that a simple relationship exists between the radial distribution of vorticity in the rolled-up wake and the spanwise lift distribution. Computed tangential velocity profiles for DC-7, DC-9, and C-141 aircraft are shown to compare favorably with profiles measured by the FAA during tower flyby tests of these aircraft in both flapped and unflapped configurations.

Donaldson, C. duP., Snedeker, R. S. and Sullivan, R. D.

"CALCULATION OF AIRCRAFT WAKE VELOCITY PROFILES AND COMPARISON WITH EXPERIMENTAL RESULTS"

Journal of Aircraft, Vol. 11, No. 9, September 1974, pp. 547-555

A method is developed for the circulation of the initial inviscid form of rolled-up wake vortices behind a wing having arbitrary lift distribution. The method makes use of the Betz assumptions of conservation of wake vorticity and moments of vorticity. It is found that a simple relationship exists between the radial distribution of vorticity in the rolled-up wake and the spanwise lift distribution. Computed tangential velocity profiles for DC-7, DC-9, and C-141 aircraft are shown to compare favorably with profiles measured by the FAA during tower flyby tests of these aircraft in both flapped and unflapped configurations.

Donaldson, C. duP., Snedeker, R. S. and Sullivan, R. D.

"CALCULATION OF THE WAKES OF THREE TRANSPORT AIRCRAFT IN HOLDING, TAKEOFF, AND LANDING CONFIGURATIONS AND COMPARISON WITH EXPERIMENTAL MEASUREMENTS"

FAA-RD-73-42, March 1973, Aeronautical Research Assoc. of Princeton, Princeton, N.

A method is described for the calculation of the initial form and location of the inviscid rolled-up wake vortices behind wings having both simple and complex load distributions such as those which occur when the wing is highly flapped. The method makes use of the Betz theorems of conservation of

vorticity and moments of vorticity in the wake. It is found that a simple relationship exists between the radial distribution of vorticity concentrated in the wake vortices and the spanwise distribution of vorticity shed from the wing. Velocity profiles computed for the vortices of several aircraft in holding, takeoff, and landing configurations are shown to compare favorably with those measured at times up to one minute after fly-by during full-scale experiments.

Donaldson, C. duP., Williamson, G. C., Bilanin, A. J. and Snedeker, R. S.

"STUDY OF THE FEASIBILITY OF CONDUCTING A WAKE-RIDING EXPERIMENT USING A T-2 AIRCRAFT BEHIND TWO P-3 AIRCRAFT"

ARAP-287, August 1976, Aeronautical Research Assoc. of Princeton, Princeton, NJ.

A study has been made of a T-2 aircraft attempting to establish a wake-riding position behind two P-3 aircraft. The major objectives were to estimate structural loads in the wake rider and to evaluate wake entry and station keeping control techniques. The results of the study indicate that the root-bending load on the tail of the T-2 aircraft would be of the order of the design load if the aircraft were to inadvertently pass directly through the center of a trailing vortex from one of the P-3's. Thus, the flight tests, as originally envisaged, must be considered as high-risk experiments unless the tail of the T-2 were to be strengthened. If wake riding experiments are carried out, approach to the wake-riding position should be made from above using a reduced-power, constant-airspeed approach. In calm air the piloting task appears reasonable if the trailing vortices are marked by smoke or condensation.

Dong, Y., Yang, Y. and Liu, C.

"DNS STUDY ON THREE VORTEX IDENTIFICATION METHODS"

AIAA Paper 2017-0137, January 2017, Grapevine, TX.

Vorticity, vorticity line and vorticity tube have rigorous definitions, but vortex has not been mathematically defined yet. It is realized that vortex is not vorticity tube and must be given a more rigorous definition, at least by some accurate identification methods. The current paper compares two popular vortex identification methods, Q-criterion and Λ^2 with the new Omega vortex identification method by visualization of several examples studied by direct numerical simulation (DNS) and large eddy simulation for flows with different speeds. The comparisons show the Omega method is much close to give vortex a mathematical definition and better visualization for vortical structures. The Omega method is quite universal and has no need to set up a threshold case by case. Additional advantages include easiness to perform, clear physical meaning, and high capability to capture both strong and weak vortices, which make Omega the most effective and efficient tool in vortex identification.

Donnadieu, C., Chomaz, J.-M. and Ortiz, S.

"INSTABILITIES AND TRANSIENT GROWTH OF TRAILING VORTICES IN STRATIFIED FLUID"

The wake, which forms behind an aircraft due to its lift, is a pair of horizontal counter-rotating vortices propagating downwards. Depending on the atmospheric conditions, such dipole can persist over a long time or be rapidly destroyed. This vortex pair, in homogeneous fluids, is unstable with respect to three-dimensional perturbations. Crow has discovered a long-wavelength instability, symmetric with respect to the plane separating the two vortices. The existence of a short-wavelength elliptic instability has been revealed by Tsai and Widnall. Moore and Saffman and numerous articles ever since have discussed both symmetric and antisymmetric modes. Recently Donnadieu et al observed a novel oscillatory instability, less unstable than Crow and elliptic modes, for large Reynolds numbers. However, in many atmospheric situations, as such dipoles propagate downwards, they evolve under the influence of the stable stratification of the atmosphere. The three-dimensional dynamics of this vortex pair in stratified flow, has received much less attention: still Robins and Delisi and Garten et al. have discussed persistence of the Crow instability and Nomura et al. of the short-wavelength instability.

Donnadieu, C., Ortiz, S., Chomaz, J.-M. and Billant, P.

"THREE-DIMENSIONAL INSTABILITIES AND TRANSIENT GROWTH OF A COUNTER-ROTATING VORTEX PAIR"

Physics of Fluids, Vol. 21, 2009, p. 094102-1 to 094102-16.

This paper investigates the three-dimensional instabilities and the transient growth of perturbations on a counter-rotating vortex pair. The two-dimensional base flow is obtained by a direct numerical simulation initialized by two Lamb-Oseen vortices that quickly adjust to a flow with elliptic vortices. In the present study, the Reynolds number is taken large enough for the quasi-steady assumption to be valid. Both the direct linearized Navier-Stokes equation and its adjoint are solved numerically and used to investigate transient and long-time dynamics. The transient dynamics is led by different regions of the flow, depending on the optimal time considered. At very small times compared to the advection time of the dipole, the dynamics is concentrated on the points of maximal strain of the base flow, located at the periphery of the vortex core. At intermediate times, depending on the symmetry of the perturbation, one of the hyperbolic stagnation points provides the optimal amplification by stretching of the perturbation vorticity as in the classical hyperbolic instability. The growth of both short time and intermediate time transient perturbations are non- or weakly dependent on the axial wavenumber whereas the long-time behavior strongly selects narrow bands of wavenumbers. We show that, for all unstable spanwise wavenumbers, the transient dynamics last until the nondimensional time $t=2$, during which the dipole has traveled twice the separation distance between vortices b . During that time, all the wavenumbers exhibit a transient growth of energy by a factor of 50, for the Reynolds number 2000. For time larger than $t=2$, energy starts growing at a rate given by the standard temporal stability theory. At large Reynolds number, the computed Crow and elliptic instability branches are in excellent agreement with the inviscid theory and numerical analysis.

Donnelly, M. J., Vlachos, P. and Telionis, D. T.

"A VORTEX PAIR IMPINGING ON A SOLID BOUNDARY"

AIAA Paper No. 1998-0690, Reno, NV, January 1998

An experimental investigation is conducted which considers the interaction of a vortex pair propagating towards a solid boundary. This problem holds significance in several engineering applications including investigations into trailing wing tip vortices and their interaction with the ground. Data are acquired with both a high-speed digital video camera and a laser Doppler velocimetry system (LDV). The digital video camera is used to capture the development and trajectory of one of the primary vortices for a variety of pitch rates. The flow field is assumed to be symmetric and only half of it is investigated. The LDV system measures two components of velocity in a plane at the center of the vortex generating flaps. Grids of data were acquired for three pitch rates and a variety of locations. It is determined that the initial vortex trajectory behaves very much like an inviscid analysis of this problem. Upon development of a secondary vortex, due to separation at the wall, the primary vortex is seen to meander and even stall.

Donohue, G. and Shortle, J.

"APPLICATION OF TOPAZ AND OTHER STATISTICAL METHODS TO PROPOSED USA CONOPS FOR REDUCED WAKE VORTEX SEPARATION"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

Wake turbulence is a major cause of terminal delays. This is particularly true during Instrument Meteorological Conditions (IMC). NASA and the FAA have recently proposed a research plan to improve airport capacity related to these standards. The plan includes near-term solutions (e.g., modification of the 2,500-foot separation standard for independent operations on closely spaced parallel runways during IMC), mid-term solutions (e.g., use of weather sensitive procedures to account for cross-winds), and far-term solutions (e.g., a dynamic wake-avoidance tool to optimize in-trail spacing based on weather conditions). This talk discussed plans to apply the TOPAZ (Traffic Organizer and Perturbation AnalyZer) safety modeling methodology to analyze proposed USA concepts of operations for reduced wake vortex separation. To motivate the methodology, we first present an application of statistical techniques used by the methodology in the analysis of simultaneous runway occupancy and runway collision probabilities at Atlanta Hartsfield Airport. We then discuss ways to extend the methodology to predict the probabilities of severe wake vortex encounters under the proposed reduced separations.

Donohue, G. L.

"THE EFFECT OF AIRCRAFT WAKE VORTEX SEPARATION ON AIR TRANSPORTATION CAPACITY"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

The wake vortex separation problem has been known for over 30 years. The current system of static restrictions and approach separation criteria reduces the air transportation system capacity under IFR conditions. In the US, these static restrictions are frequently ignored under VMC conditions by assigning aircraft separation responsibility to the pilot once he has the airport runway in sight. The current system leads to 1) frequently imposing excessive separation under IMC and 2) infrequently allowing inadequate separation under VMC. The recent NASA/FAA research on wake vortex separation has made significant progress on both theoretical understanding and empirical measurement of the aircraft wake vortex behavior interacting with the atmospheric boundary layer. The current state-of-the-art indicates that new sensors and vortex prediction and warning algorithms should be incorporated into FAA weather and ATM decision support system software to recover critical lost air transportation capacity while at the same time maintaining or increasing safety. Runway wind directional variability is intrinsic to the random nature of the atmospheric turbulent boundary layer. This inherent uncertainty in wind vector presents challenges to accurately predicting runway wind direction out to 30 minutes. The prediction time is required to begin the spacing of arriving aircraft approximately 200 miles from the airport due to the aircraft maneuver restrictions. The atmospheric turbulent boundary layer Turbulent Kinetic Energy (TKE) level or eddy dissipation level is a more stable scalar quantity and is more reliable in predicting the conditions for wake vortex breakup and accelerated circulation decay. Based upon both the experimental results observed in the NASA DFW experiments and theoretical considerations, it is recommended that the FAA Integrated Terminal Weather System (ITWS) be upgraded to initially provide a WARNING of wake vortex circulation intensity above background. It is suggested that this is a better criterion for any wake vortex ATC system, NOT a PREDICTION of wake vortex location relative to the runway centerline for initial system implementations. This system should work well under most windy conditions. Under low wind, stable IMC conditions, the wind conditions may be more predictable and wake centerline prediction may provide more additional capacity.

Donzier, A.

"WAKE VORTEX DETECTION USING A PHASED ARRAY SODAR"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 39-1 - 39-10

Following the study of windshear at Roissy International Airport, using a REMTECH PA3 phased array system tilted at low elevation angles, the system was used to investigate wake vortex intensity using acoustic techniques. The PA3 system was installed at Roissy/Charles de Gaulle Airport on April 22, 1991, with a revised software version allowing the emission of 5 frequencies in a single acoustic pulse. The sounding range was set from 50 m to 1 km. The averaging time was set to 5 minutes. The system is operating continuously and data are stored on the hard disk. Strong echo regions are observed, but need to be studied to determine the source of the scattering.

Doolan, C. J., Coton, F. N. and Galbraith, R. A. McD.

"MEASUREMENT OF THREE-DIMENSIONAL VORTICES USING A HOT WIRE ANEMOMETER"

AIAA Paper No. 1999-3810, Norfolk, VA, June 1999

A series of tests were performed using a new vortex generator rig in the 1.15 m x 0.85 m low speed wind tunnel at Glasgow University. Results were acquired with a hot wire anemometer system using single and cross wire probes. A strong vortex velocity field was measured which confirmed the success of the vortex generation techniques and provided information about features of the flow. An interaction occurred between the vortex core and the hot wire probe which manifested itself as variations in vortex core measurements which one would not expect without probe interference. While an interaction was present when measuring close to the viscous core region, in the inviscid external field the probe had little effect on vortex dynamics. This allowed analysis of vortex geometry and an estimation of the vortex wandering amplitude in the test section. The curvature of the vortex generator wake was also measured using differently spaced single and cross wire probes. The data were compared with a computational model and showed good agreement.

Doolan, C. J., Coton, F. N. and Galbraith, R. A. M.

"SURFACE PRESSURE MEASUREMENTS OF THE ORTHOGONAL VORTEX INTERACTION"

AIAA Journal, Vol. 39, No. 1, January 2001, pp. 88-95.

A unique vortex generator that simulates the trailing vortex produced by a helicopter main rotor in forward flight was used in a study of main rotor/tail rotor blade vortex interaction. Velocity measurements were performed using hot wire anemometry and particle image velocimetry, which showed the interacting vortices to be three dimensional and to contain a significant core axial flow. Surface pressure measurements during vortex collision with an instrumented, stationary blade were obtained at a variety of incidence settings. At the leading edge, a suction peak occurred where the core flow was directed away from the surface and, similarly, a pressure peak occurred where the core flow was directed toward the surface. This behavior can be explained in terms of the impulsively blocked vortex core axial flow. Also, the leading-edge suction and pressure peaks were amplified or attenuated by changing the incidence of the blade. However, the changes in surface pressure distribution were such that the peak normal force was approximately the same for each incidence setting.

Doran, P.

"STUDY OF INSTABILITY OF AIRCRAFT WAKE VORTICES IN GROUND EFFECT"

PhD Thesis, July 2017, University of Quebec, Montreal, Canada [In French].

With the increasing use of air transport for passengers, traffic increasingly dense near airports is formed. The wake of each aircraft represents a potential threat to the stability of a plane in the vicinity of this wake. This threat is even greater when the plane is near the ground, as in the case of an aircraft in landing and takeoff phase. To minimize risks, a safe distance must be imposed between the aircraft leader and follower aircraft. To increase air traffic, the distance should be minimized. To do this, a

study of the wakes' natural dissipation mechanisms in ground effect is achieved. This study is obtained by numerical simulations and linear stability analyses of a pair of counter-rotating vortices. DNS models the configuration of a pair of counter-rotating vortices in ground effect, while the analytical stability study models a pair of counter-rotating out of ground effect. It is noted for in ground effect configuration the main vortices of the pair mutually induce a downward velocity. At ground approach, boundary layers are formed and eventually separated to become secondary vortices whose circulations are less than the principal's. The study of the vortex perturbation field from the numerical results shows a typical bending mode instability in the secondary vortices and the beginning of the appearance of an elliptical instability in the main vortices. In addition, the study of the linear stability of the subsystem consists of a primary vortex and secondary vortex which corroborates the wave numbers identified using numerical simulations. Now, it is deduced that only the ratio of circulations and the radius of the secondary vortex are needed to predict the most unstable wave number from theoretical analysis of stability the vortex system. Subsequently, the effect of a side wind is considered. The effect of the wind is equivalent to adding a background vorticity. This background vorticity has the effect of making the vortex system asymmetric. The left and right vortex subsystems, each composed of a main vortex and a secondary vortex, interact differently depending on the vorticity resulting from the superposition of the background vorticity and that of the subsystem. In this in ground effect configuration with a crosswind, the ratio of circulation and the radius of the secondary vortex are evaluated. These two parameters are used to determine, with the same linear stability theory outlined above, the most unstable wave number leading to the dissipation of the aircraft wake vortices.

Dosanjh, D. S. and Weeks, T. M.

"INTERACTION OF A STARTING VORTEX AS WELL AS A VORTEX STREET WITH A TRAVELING SHOCK WAVE"

AIAA Journal, Vol. 3, No. 2, 1965, pp. 216-223.

The passage of a shock front and the associated drift flow over a two-dimensional airfoil, at an angle of attack mounted in a shock tube, generated a columnar spiral starting vortex that interacted with the normal reflected shock. Interferometric investigations of this interaction extended considerably earlier schlieren observations by Hollingsworth and Richards. The generation of a progressive cylindrical acoustic wave front centered on the transmitted vortex and its alternate compression-rarefaction nature, as predicted by linearized analyses by Hollingsworth and Richards and later by Ribner, was experimentally verified and deviations from the predicted pressure amplitude distribution were discovered. A semiempirical relation for the wave-front pressure-amplitude distribution (expressed as a linear combination of quadrupole, dipole, and monopole acoustic sources) was found to represent closely the experimental results. The time variation of the core density of the transmitted vortex was deduced. The spiral vortex decayed essentially as a circular, incompressible viscous vortex until a neighboring high-density region appeared and the vortex decayed at a faster rate. The interaction of the reflected shock with the vortex street generated behind a circular cylinder, resulted in an abrupt change in vortex spacing and rapid dissolution of the vortex street. No well-defined acoustic wave fronts were evident behind the reflected shock front.

Dosanjh, D. S., Gasparek, E. P. and Eskinazi, S.

"DECAY OF A VISCOUS TRAILING VORTEX"

Aero. Quarterly, Vol. 13, May 1962, pp. 167-188

An experimental investigation of the viscous decay of a steady three-dimensional helical vortex is presented. The vortex was generated by a rectangular, symmetrical half airfoil, cantilevered from the wall of the circular test section of a low-speed wind tunnel. Only the local total head and flow directions were measured with a five-hole pressure sensitive probe at one to eight chord lengths behind the trailing edge of the airfoil and the radial, tangential and axial velocity distributions in the trailing vortex were derived. The static pressure variation on the vortex flow and the difficulties in its accurate measurement are discussed.

Dougherty, R. P.

"EXTENSIONS OF DAMAS AND BENEFITS AND LIMITATIONS OF DECONVOLUTION IN BEAMFORMING"

AIAA Paper No. 2005-2961, Monterey, CA, May 2005

The DAMAS deconvolution algorithm represents a breakthrough in phased array imaging for aeroacoustics, potentially eliminating sidelobes and array resolution effects from beamform maps. DAMAS is an iterative non-negative least squares solver. The original algorithm is too slow and lacks an explicit regularization method to prevent noise amplification. Two extensions are proposed, DAMAS2 and DAMAS3. DAMAS2 provides a dramatic speedup of each iteration and adds regularization by a low pass filter. DAMAS3 also provides fast iterations, and additionally, reduces the required number of iterations. It uses a different regularization technique from DAMAS2, and is partially based on the Wiener filter. Both DAMAS2 and DAMAS3 restrict the point spread function to a translationally-invariant, convolutional, form. This is a common assumption in optics and radio astronomy, but may be a serious limitation in aero-acoustic beamforming. This limitation is addressed with a change of variables from (x,y,z) to a new set, (u,v,w) . The concepts taken together, along with appropriate array design, may permit practical 3D beamforming in aeroacoustics.

Dougherty, R. P., Wang, F. Y., Booth, E. R., Watts, M. E., Fenichel, N. and D'Errico, R. E.

"AIRCRAFT WAKE VORTEX MEASUREMENTS AT DENVER INTERNATIONAL, AIRPORT"

AIAA Paper No. 2004-2880, Manchester, UK, May 2004.

Airport capacity is constrained, in part, by spacing requirements associated with the wake vortex hazard. NASA's Wake Vortex Avoidance Project has a goal to establish the feasibility of reducing this spacing while maintaining safety. Passive acoustic phased array sensors, if shown to have operational potential, may aid in this effort by detecting and tracking the vortices. During August/September 2003, NASA and the USDOT sponsored a wake acoustics test at the Denver International Airport. The central instrument of the test was a large microphone phased array. This paper describes the test in general terms and gives an overview of the array hardware. It outlines one of the analysis techniques that is

being applied to the data and gives sample results. The technique can clearly resolve the wake vortices of landing aircraft and measure their separation, height, and sinking rate. These observations permit an indirect estimate of the vortex circulation. The array also provides visualization of the vortex evolution, including the Crow instability.

Douxchamps, D.

"MULTIDIMENSIONAL PHOTOGRAMMETRY OF SHORT-LIVED EVENTS"

PhD Thesis, October 2004, Universite Catholique de Louvain, Louvain-la-Neuve, Belgium.

We have presented three photogrammetry techniques that successfully capture different short-lived events of increasing complexity. First, we have shown that the first simple unidimensional motion of vehicles on a highway can be analyzed with accuracy by a set of two line-scan cameras. This new technique also provides much other information about the traffic, making it a very good choice both for traffic management and law enforcement. The second theme developed shows how a close relationship between the fluid mechanics and the vision techniques can lead to a better confidence in the measurements compared to what would be obtained by each method individually. The recent advances in the theoretical formulation of the anti-dunes behavior will have to be compared with surfaces like the ones presented here, although the unstable and evolutive character of this phenomenon will make this task far from trivial. At last, a new model for the spectrum returned by an on-board lidar is compared with several other spectral estimation approaches. The higher performance of the model enables the detection of the aircraft wake vortices that were sought.

Douxchamps, D., Lugan, S., Verschueren, Y., Mutuel, L., Macq, B. and Chihara, K.

"ON-BOARD AXIAL DETECTION OF WAKE VORTICES USING A 2-MICRON LIDAR"

IEEE Transactions on Aerospace and Electronic Systems, Vol. 44, No. 4, Oct. 2008, pp. 1276-1290.

This paper describes the first successful attempt to detect wake vortices axially using an on-board infrared pulsed Doppler LiDAR. On-board axial detection is more complex than the classic ground-based tangential approach, because the axial air speed in vortices is low and the atmospheric particle density is reduced, yielding a poorer SNR. To provide meaningful results in such unfavorable conditions we have developed a new flexible signal processing method based on a two-primitive model fitting the spectrum of the Doppler return. This new spectral estimation successfully detects wake vortices with an admissible SNR that is lower than other on-board state-of-the-art approaches. It was validated through flight tests.

Doyle, J. D., Jiang, Q. and Reinecke, P. A.

"NUMERICAL MODELING AND PREDICTABILITY OF MOUNTAIN WAVE-INDUCED TURBULENCE AND ROTORS"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 18, 2016, Springer International Publishing Switzerland, pp. 357-384.

A survey is provided of a series of studies that demonstrate the capabilities of modern nonhydrostatic numerical models to simulate and predict the occurrence of mountain waves, wave-induced turbulence in the upper troposphere and stratosphere, and rotors in the lower troposphere generated by flow over topography. Field campaign measurement from research aircraft, turbulence reports from commercial aviation, and numerical simulations demonstrate that flow over larger-scale topography (e.g., Greenland) and three-dimensional complex terrain (e.g., Alps, Sierra Nevada Range) frequently generates upper-level wave breaking and turbulence in a variety of conditions including in the presence of environmental critical levels. In some situations, the boundary layer can strongly influence wave launching, and may limit wave amplitudes and impact the altitude and likelihood of wave breaking and turbulence. Near the surface, rotors occur when strong downslope flow in the boundary layer along the lee slopes separate from the surface as a turbulent vortex sheet, which is lifted aloft within the lee wave. Because of their strong turbulent flow, rotors are often significant aeronautical hazards. The predictive skill of numerical simulations of mountain wave-induced turbulence observed in nature is limited by errors in initial conditions, boundary conditions (e.g., for limited area models), and the models themselves (e.g., parameterizations, dynamical methods). Ultimately, high-resolution ensemble methods that are capable of explicitly resolving mountain waves should be used to provide probabilistic forecasts of turbulence needed for aviation hazard mitigation.

Draghicescu, C. I. and Draghicescu, M.

"A FAST ALGORITHM FOR VORTEX BLOB INTERACTIONS"

Journal of Computational Physics, Vol. 116, 1995, pp. 69-78

We introduce a new fast summation algorithm which, unlike previous methods, is not restricted to potential functions. Its asymptotic complexity is $O(nH, H \text{ to the } d+1 \text{ power})$, where n is the number of blobs, H is the level of refinement, and d is the domain dimension. For a nonsingular kernel the complexity reduces to $O(n)$. We present a complete error and complexity analysis of the algorithm and describe its implementation. As an example, we use the vortex blob method to simulate vortex sheet motion in incompressible flow.

Drasky, J.

"ON SOME PARTICULAR CASES OF THE SOLUTION OF LAPLACE'S EQUATION DESCRIBING THE PRINCIPAL PROPERTIES OF VORTEX FORMATIONS IN FLUIDS"

Zeitschrift fur Angewandte Mathematik und Mechanik, Vol. 46, No. 2, 1966, pp. 81-95.

Vortex formations represent a particular case of discontinuous flow of fluids. For the most, they are non-stationary formations with a pronounced whirling motion of intensity that is characterized by velocity circulation about the center, decreasing or increasing with time. They always contain a core with a marked component of rotational motion and one or two discontinuity surfaces or vortex layers

rolling up in the form of spirals. In addition to the intensive whirling motion, they also exhibit centripetal or centrifugal motions. For cases where in the first approximation the effect of viscosity may be neglected and the medium considered an incompressible fluid, the paper demonstrates that all basic features of vortex formations may be described by a solution of Laplace's equation constructed as a convenient combination of algebraic and logarithmic singularities. The solution thus obtained is dependent on time insofar that all conditions of compatibility of the flow must be satisfied at all times in every point (particularly on the discontinuity surface). Several plane models of vortex formations are considered and with their aid a model is constructed of a flow field with vortex pair behind a cylinder starting from rest. A comparison of theoretical and experimental results is presented for this case.

Drew, D. R., Barlow, J. F. and Lane, S. E.

"OBSERVATIONS OF WIND SPEED PROFILES OVER GREATER LONDON, UK, USING A DOPPLER LIDAR"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 121, 2013, pp. 98-105.

To calculate the potential wind loading on a tall building in an urban area, an accurate representation of the wind speed profile is required. However, due to a lack of observations, wind engineers typically estimate the characteristics of the urban boundary layer by translating the measurements from a nearby reference rural site. This study presents wind speed profile data obtained from a Doppler lidar in central London, UK, during an 8-month observation period. Used in conjunction with wind speed data measured at a nearby airport, the data have been used to assess the accuracy of the predictions made by the wind engineering tools currently available. When applied to multiple changes in surface roughness identified from morphological parameters, the non-equilibrium wind speed profile model by Deaves provides a good representation of the urban wind speed profile. For heights below 500 m, the predicted wind speed remains within the 95 percent confidence interval of the measured data. However, when the surface roughness is estimated using land use as a proxy, the model tends to overestimate the wind speed, particularly for very high wind speed periods. These results highlight the importance of a detailed assessment of the nature of the surface when estimating the wind speed above an urban surface.

Drikakis, D., Grinstein, F. and Youngs, D.

"ON THE COMPUTATION OF INSTABILITIES AND SYMMETRY-BREAKING IN FLUID MECHANICS"

Progress in Aerospace Sciences, Vol. 41, Issue 8, November 2005, pp. 609-641

A review on the implementation of modern computational fluid dynamics (CFD) methods for simulating low- and high-speed flows featuring turbulent mixing, instabilities and symmetry-breaking is presented. Results are reviewed for several complex flows including turbulent mixing associated with Richtmyer-Meshkov and Raleigh-Taylor instabilities, incompressible flows in suddenly expanded geometries, shock-induced instabilities, free-shear instabilities, and complex vortex dynamics. Many of the results presented in this review have been obtained by large eddy simulation (LES), monotone

integrated LES (MILES) in particular. The computational challenges associated with complex flow physics and nonlinear behaviour of the numerics are discussed.

Dritschel, D. G.

"ON THE PERSISTENCE OF NON-AXISYMMETRIC VORTICES IN INVISCID TWO-DIMENSIONAL FLOWS"

Journal of Fluid Mechanics, Vol. 371, 1998, pp. 141-155.

Previous research has suggested that isolated, initially non-axisymmetric vortices in two-dimensional flows tend to become axisymmetric, in a coarse-grained sense, by purely inviscid mechanisms. That research, however, considered only vortices with broadly distributed vorticity. In this paper, it is shown that vortices with sufficiently steep edge gradients behave in a radically different way; in particular, they can remain non-axisymmetric, apparently indefinitely. Such vortices, it is argued, are more typical in inviscid two-dimensional flows than the broadly distributed vortices previously considered, and hence the tendency for vortices to become axisymmetric is not generic to these flows.

Dritschel, D. G.

"A GENERAL THEORY FOR TWO-DIMENSIONAL VORTEX INTERACTIONS"

J. Fluid Mech., Vol. 293, June 1995, pp. 269-303

A general theory for two-dimensional vortex interactions is developed from the observation that, under slowly changing external influences, an individual vortex evolves through a series of equilibrium states until such a state proves unstable. Once an unstable equilibrium state is reached, a relatively fast unsteady evolution ensues, typically involving another nearby vortex. During this fast unsteady evolution, a fraction of the original coherent circulation is lost to filamentary debris, and, remarkably, the flow reorganizes into a set of quasi-steady stable vortices. The simplifying feature of the proposed theory is its use of adiabatic steadiness and marginal stability to determine the shapes and separation distances of vortices on the brink of an inelastic interaction. In the case of two vortex patches, which is the focus of the present work, inelastic interactions depend only on a single parameter: the area ratio of the two vortices (taking the vorticity magnitude inside each to be equal). Without invoking adiabatic steadiness and marginal stability, one would have to contend with the additional parameters of vortex separation and shapes and the latter is actually an infinitude of parameters.

Droandi, G., Zanotti, A., Gibertini, G., Grassi, D. and Campanardi, G.

"EXPERIMENTAL INVESTIGATION OF THE ROTOR-WING AERODYNAMIC INTERACTION IN A TILTWING AIRCRAFT IN HOVER"

The Aeronautical Journal, Vol. 119, No. 1215, May 2015, pp. 591-612.

The hovering performance and the lifting capability of tiltrotor aircraft are strongly affected by the aerodynamic interaction between wing and rotors. The tiltwing concept represents a promising

technology to increase the hover performance by reducing the wing-rotor interference. The present work describes an experimental activity carried out on a 1/4 scaled tiltwing aircraft half-model to achieve a detailed insight about the main issues characterizing the aerodynamic interaction between wing and rotor in hover. The results of the experimental campaign, including both force measurements and Particle Image Velocimetry surveys, enabled to evaluate both the aircraft performance for different configurations of the tilting wing and to achieve a detailed insight about the flow physics of the rotor wake in the interaction with the wing. The test activity provided a comprehensive experimental database that was obtained over a not confidential aircraft configuration.

Drue, C., Hauf, T. and Hoff, A.

"COMPARISON OF BOUNDARY-LAYER PROFILES AND LAYER DETECTION BY AMDAR AND WTR/RASS AT FRANKFURT AIRPORT"

Boundary-Layer Meteorology, Vol. 135, 2010, pp. 407-432.

At Frankfurt Airport vertical soundings of the lower atmosphere from two independent sources are available. One of them is a wind and temperature profiler (wind temperature radar and radio acoustic sounding system, WTR/RASS) located at the western end of the main pair of runways. The second source is aircraft meteorological data relay (AMDAR), i.e. measurements operationally collected by approaching and departing aircraft. Together, both offer a rare opportunity to compare the performance of these widely used systems. We use 1 year of continuous data to calculate systematic temperature and wind vector differences between both measurement systems. The differences show a clear season-dependent structure in conjunction with typical inversion heights. Possible causes for this behavior are discussed. Second, we compare the ability of both systems to identify inversion and wind-shear layers above the airport. AMDAR-detected layers are typically higher than wind profiler detections. The layer base is usually detected with more agreement than the top. The mutual probability of detection of inversions is found to be mostly between 40 and 60 percent.

Drummond, A. M., Onno, R. and Panneton, B.

"TRAJECTORIES AND STABILITY OF TRAILING VORTICES VERY NEAR THE GROUND"

IAR-AN-74, December 1991, Inst. Aerospace Research, Ottawa, Canada

The behavior of the trailing vortices of a Harvard aircraft used as the spraying vehicle during a set of experiments in aerial spraying over flat terrain for agricultural applications is discussed. The aircraft flew at a nominal altitude of 3 m (10 ft.) above ground at a speed of 56.7 m/s (110 knots). The stability and trajectory of a chosen element of the trailing vortices were measured by analyzing movie films taken by a ground-based camera and by a camera in a helicopter hovering at about 244 m (800 ft.) above the aircraft. The vortices decayed by core bursting in every case and the time to burst was usually in agreement with other published data for a light aircraft out of ground effect. The downwind vortex almost always burst before the upwind vortex and in most cases, both upwind and downwind vortices exhibited about the same amount of rebound even though the downwind vortex generally had

a shorter lifetime. The classical inviscid theory for vortex descent was not a good model for the current experiments but it was able to predict with some success the lateral separation between the vortices when the aircraft wing tip height was arbitrarily reduced by a factor of 0.85. It was concluded that vortex core bursting and rebound must be included in any procedure for calculating aerial spray deposit on the ground.

Duan, H., Zhang, Q., Fan, Y., and Li. H.

"HARDWARE-IN-LOOP SIMULATION PLATFORM FOR UAV AUTONOMOUS AERIAL REFUELING BASED ON COMPUTER VISION"

Journal of Beijing University of Aeronautics and Astronautics, Vol. 39, No. 11, November 2013, pp. 1491-1496.

A hardware-in-loop simulation platform of unmanned aerial vehicle (UAV) autonomous aerial refueling based on computer vision was developed. Point feature matching and LHM pose estimation algorithms were adopted to the recognition of light emitting diodes (LEDs) on the drogue. The models of atmospheric disturbances and wake vortex had been built, and the drogue model was also presented. Subsequently, a linear quadratic regulator (LQR) control law for UAV was designed. The hardware-in-loop simulation platform with airborne monocular camera for UAV autonomous aerial refueling had been developed in lab environment. Series of hardware-in-loop experimental results demonstrate the feasibility and effectiveness of our presented approaches in this simulation platform. [In Chinese.]

Duck, P. W.

"ON THE DOWNSTREAM DEVELOPMENT AND BREAKUP OF SYSTEMS OF TRAILING-LINE VORTICES"

Theoretical Computational Fluid Dynamics, Vol. 25, 2011, pp. 43-52.

The downstream evolution of two configurations of trailing-line vortex systems is considered and analyzed from the point of view of bi-global instability. The results lead to predictions for the breakup of the systems considered, based primarily on stability analysis. Throughout, the analysis is entirely rational from the theoretical (asymptotic, large Reynolds number) point of view, with a relatively long developmental length scale in the streamwise direction for the base flow, and a relatively short streamwise wavelength for the bi-global stability analysis. As such, the stability modes are inviscid in nature, and therefore likely to be one of the dominant instability mechanisms. The issue of adverse streamwise freestream pressure gradients is also addressed, and it is suggested that these can lead to a rapid breakdown/up of a vortex system, analogous to the axisymmetric case discussed by Hall (1972).

Duck, P. W. and Khorrami, M. R.

"A NOTE ON THE EFFECTS OF VISCOSITY ON THE STABILITY OF A TRAILING-LINE VORTEX"

J. Fluid Mech., Vol. 245, December 1992, pp. 175-189

The linear stability of the Batchelor vortex is investigated. Particular emphasis is placed on modes found recently in a numerical study by Khorrami. These modes have several features very distinct from those found previously for this vortex, including (i) exhibiting small growth rates at large Reynolds number and (ii) susceptibility to destabilization by viscosity. In this paper these modes are described using asymptotic techniques, producing results which compare very favorably with fully numerical results at large Reynolds numbers.

Duffy, R. E., Czajkowski, E. A. and Jaran, C.

"FINITE ELEMENT APPROXIMATION TO THEODORSEN'S SOLUTION FOR NON-STEADY AERODYNAMICS OF AN AIRFOIL SECTION"

AIAA Paper No. 1984-1640, Snowmass, CO, June 1984

The aerodynamic forces acting on a helicopter rotor blade have been calculated by several investigators using finite element methods and theories. All these results depend to some extent on the proper modeling of the wake behind the rotor blade. To evaluate the importance of proper modeling of the near wake behind a rotor blade, a simpler, but related, problem is addressed -- namely the modeling of the flow field about a two-dimensional, flat plate airfoil section which is undergoing simple harmonic motion in both vertical translation and pitch. An exact closed form solution of this problem has been obtained by Theodorsen. This study evaluates how the circulation on the airfoil and in the wake has to be modeled to predict the proper value of lift and pitching moment as determined by Theodorsen. The goal is to use the least number of elements in the model. It is shown that it is only necessary to follow the wake, at most, one cycle length downstream. The cycle length can be divided as coarsely as ten increments and as few as two and no more than ten wake vortex filaments must be considered. The accuracy of prediction decreases slightly as the number of bound vortex lifting lines increases.

Dufresne, L. and Winckelmans, G.

"PREVIOUS WORK AND PRESENT KNOWLEDGE ON WAKE VORTICES NEAR THE GROUND"

AST4-CT-2005-012238, Catholic Univ. of Leuven, Leuven, Belgium, July 2005

The understanding of the formation and decay of wake vortex systems has indeed greatly progressed over the years. The knowledge was mostly developed though for free vortex systems, i.e. far from any ground proximity (or 'out of ground effect' OGE). When considering wake vortex dynamics from the stand point of safety delays between aircrafts taking-off or landing, ground proximity will most certainly, sooner or later, affect the wake vortex behavior. Considering the research objectives for the wake vortex evolution near the ground, which constitute the Work-Package 3 of the FAR-Wake project, the present report aims at giving a synthesis of past work and present knowledge on this particular subject.

Duke, T.

"TRAINING TO BEAT WAKE TURBULENCE"

Air Line Pilot, Vol. 64, No. 8, September 1995, pp. 20-24.

Recently, a cooperative effort involving FAA, the Boeing Company, and a joint industry group (including ALPA) developed training materials. The training kit consists of a 430-page comprehensive, well-illustrated manual titled: 'Wake Turbulence Training Aid' in printed or CD ROM disc form and an accompanying videotape.

Dumitrescu, H. and Frunzulica, F.

"A FREE-WAKE AERODYNAMIC MODEL FOR HELICOPTER ROTORS"

Proceedings of the Romanian Academy, Series A, Vol. 5, No. 3, 2004, pp. 1-9.

The accurate computation of the induced velocity on helicopter rotor plane is a prerequisite for the precise evaluation of the angle of attack distribution along the rotor blades, which leads to improved air loads prediction for aerodynamics and aeroacoustics design and performance analysis. The Vortex Lattice Method provides a transparent investigation concerning the role of various physical parameters which influence the aerodynamic problem of rotor downwash calculation. This paper presents a method for the calculation of the nonuniform induced downwash of a helicopter rotor using the vortex ring model for a thin lifting surface coupled with a free-wake model.

Dunagan, S. E. and Norman, T. R.

"LIFT DISTRIBUTION OF VELOCITY FIELD MEASUREMENTS FOR A THREE-DIMENSIONAL, STEADY BLADE/VORTEX INTERACTION"

NASA TM-100013, November 1987, Ames Research Center, Moffett Field, CA.

A wind tunnel experiment simulating a steady three-dimensional helicopter rotor blade/vortex interaction is reported. The experimental configuration consisted of a vertical semispan vortex-generating wing, mounted upstream of a horizontal semispan rotor blade airfoil. A three-dimensional laser velocimeter was used to measure the velocity field in the region of the blade. Sectional lift coefficients were calculated by integrating the velocity field to obtain the bound vorticity. Total lift values, obtained by using an internal strain-gauge balance, verified the laser velocimeter data. Parametric variations of vortex strength, rotor blade angle of attack, and vortex position relative to the rotor blade were explored. These data are reported herein (with attention to experimental limitations) to provide a dataset for the validation of analytical work.

Duncan Jr., J. B., Hirth, B. D. and Schroeder, J. L.

"DOPPLER RADAR MEASUREMENTS OF SPATIAL TURBULENCE INTENSITY IN THE ATMOSPHERIC BOUNDARY LAYER"

Journal of Applied Meteorology and Climatology, Vol. 58, July 2019, pp. 1535-1555.

Remote sensing instruments that scan have the ability to provide high-resolution spatial measurements of atmospheric boundary layer winds across a region. However, the time required to collect the volume of measurements used to produce this spatial representation of atmospheric winds typically limits the extraction of atmospheric turbulence information using traditional temporal analysis techniques. To overcome this constraint, a spatial turbulence intensity (STI) metric was developed to quantify atmospheric turbulence intensity (TI) through analysis of spatial wind field variability. The methods used to determine STI can be applied throughout the measurement domain to transform the spatially distributed velocity fields to analogous measurement maps of STI. This method enables a comprehensive spatial characterization of atmospheric TI. STI efficacy was examined across a range of wind speeds and atmospheric stability regimes using both single- and dual-Doppler measurements. STI demonstrated the ability to capture rapid fluctuations in TI and was able to discern large-scale TI trends consistent with the early evening transition. The ability to spatially depict atmospheric TI could benefit a variety of research disciplines such as the wind energy industry, where an understanding of wind plant complex flow spatiotemporal variability is limited.

Dunham, J.

"THE STATIC PRESSURE IN A VORTEX CORE"

Aeronautical Journal, Vol. 83, October 1979, pp. 402-406.

An analysis and comparison with experimental data is given for the static core pressure of ground and wingtip vortices that might be ingested by turbine engine compressor intakes. Parameters considered include tangential velocity, turbulence, static pressure, core radius, stagnation pressure and axial velocity, along with test data from hot wire and laser velocimeters.

Dunham, Jr., R. E.

"VORTEX DISSIPATION TESTS CONDUCTED AT NASA LANGLEY RESEARCH CENTER"

Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, Air Force Flight Dynamics Laboratory, AFFDL-TM-75-16-FGC, 1974, pp. 29-35

The major interest in vortices at Langley lies in the far wake aspect of the problem, and especially in the possibility of enhancing the rate of far wake dissipation. Three separate facilities are used to conduct tests on wake vortex behavior and possible dissipation devices: the Vortex Flow Facility (an 1800-foot track), the Langley V/STOL wind tunnel, and the Hydronautics water tank facility. An overall summary of NASA Langley experiments with hazard reduction techniques was presented; the manipulation of span loading appears to be the most promising hazard reduction technique.

Dunham, Jr., R. E.

"SUMMARY OF NASA WAKE-VORTEX MINIMIZATION RESEARCH"

Proceedings Aircraft Safety and Operating Problems, NASA, Washington, DC, 1976, pp. 303-318

NASA's efforts in the area of wake-vortex minimization are reviewed. The results presented at a NASA symposium on wake-vortex minimization are summarized and additional results obtained since the symposium are included. Theoretical and experimental techniques for assessing the effectiveness of various wake-vortex minimization techniques are described. Three methods of reducing the effect of aircraft trailing vortices and a preliminary assessment of the operational suitability of employing wake-vortex minimization techniques are discussed. The application of one wake-vortex minimization technique to DC-10 and L-1011 aircraft is presented.

Dunham, Jr., R. E.

"UNSUCCESSFUL CONCEPTS FOR AIRCRAFT WAKE VORTEX MINIMIZATION"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 221-250.

Exploratory concepts are described which were investigated to achieve a reduction in the vortex induced rolling upsets produced by heavy aircraft trailing vortexes. The initial tests included the use of mass injection, oscillating devices, wingtip shape design, interacting multiple vortexes, and end plates. Although later refinements of some of these concepts were successful, initial test results did not indicate a capability of these concepts to significantly alter the vortex induced rolling upset on a following aircraft.

Dunham, Jr., R. E. and Morris, D. J.

"RECENT DEVELOPMENTS IN WAKE VORTEX MINIMIZATION"

SAE Paper No. 780524, Boston, MA, May 1978

Aircraft trailing vortices are one of the principal factors affecting aircraft arrival and departure rates at airports. Minimization of the trailed vortex strength would allow reduction of the present spacing requirements and full utilization of advances in automatically aided landing systems. For several years, NASA has been conducting an intensive in-house and contractual research effort involving theoretical and experimental studies of various wake vortex minimization techniques. The results of these studies are briefly described herein.

Dunham, Jr., R. E., Barber, M. R. and Croom, D. R.

"WAKE VORTEX TECHNOLOGY"

CTOL Transport Technology, 1978, pp. 757-771

A brief overview of the highlights of NASA's wake vortex minimization program is presented. The significant results of this program are summarized as follows: (1) it is technically feasible to reduce significantly the rolling upset created on a trailing aircraft; (2) the basic principles or methods by which reduction in the vortex strength can be achieved have been identified; and (3) an analytical capability for investigating aircraft vortex wakes has been developed.

Dunham, Jr., R. E., Holbrook, G. T., Mantay, W. R., Campbell, R. L. and Van Gunst, R. W.

"FLIGHT-TEST EXPERIENCE OF A HELICOPTER ENCOUNTERING AN AIRPLANE TRAILING VORTEX"

32nd Annual National V/STOL Forum, American Helicopter Society, Washington, DC, May 1976

This paper presents results of a flight-test experiment of a UH-1H helicopter encountering the vortex wake of a C-54 airplane. The helicopter was instrumented to record the pilot control inputs, determine the upset experienced, and measure critical loads within the rotor system. During the flight-test program 132 penetrations of the vortex wake were made by the helicopter at separation distances from 3/8 to 6-1/2 nautical miles. Test results indicated that the helicopter upsets and the vortex induced blade loads experienced were minimal and well within safe limits. The upsets were very mild when compared to a typical response of a small airplane to the vortex wake of the C-54 airplane.

Dunham, Jr., R. E., Stuever, R. A. and Vicroy, D. D.

"THE CHALLENGES OF SIMULATING WAKE VORTEX ENCOUNTERS AND ASSESSING SEPARATION CRITERIA"

AIAA Paper No. 1993-3568, Monterey, CA, August 1993.

During landings and take-offs, the longitudinal spacing between airplanes is in part determined by the safe separation required to avoid the trailing vortex wake of the preceding aircraft. Safe exploration of the feasibility of reducing longitudinal separation standards will require use of aircraft simulators. This paper discusses the approaches to vortex modeling, methods for modeling the aircraft/vortex interaction, some of the previous attempts of defining vortex hazard criteria, and current understanding of the development of vortex hazard criteria.

Dunham, Jr., R. E., Verstynen, H. A. and Banner, M. S.

"PROGRESS REPORT ON WING-TRAILING-VORTEX STUDIES"

NASA Aircraft Safety and Operating Problems, Vol. 1, NASA SP-270, 1971, pp. 101-113

The paper summarizes the activities of NASA in three major areas of vortex research. The first area is concerned with the measurement of the characteristics of full-scale aircraft vortices to obtain an understanding of the behavior of vortices at altitude and near the ground. Of particular interest are the velocities and their distributions, and the vortex persistence. The second area involves investigations of possible techniques to affect a more rapid breakdown or decay of vortices; the

deployment of wing flaps creates a vortex system which is less intense and decays more rapidly than vortices created in a flaps-up condition. The third area concerns an investigation of the feasibility of remotely detecting the presence of wing trailing vortices in the terminal area.

Dunham, Jr., R. E., Verstynen, H. A. and Banner, M. S.

"PRELIMINARY RESULTS OF A FLIGHT INVESTIGATION OF THE TRAILING VORTICES GENERATED BY A C-5A HEAVY JET TRANSPORT"

LWP-969, June 1971, NASA Langley Research Center, Hampton, VA

Some exploratory flight tests were conducted to investigate the strength and persistence characteristics of the vortices generated by a C-5A jet transport. The tests were conducted using an instrumented T-33 aircraft to probe the vortices of the C-5A while ranging information was provided by ground-based radars. The results are presented in terms of tabulated maximum measured tangential velocities and radii of maximum velocities, vortex positions as a function of distance behind the C-5A, and maximum recorded velocity as a function of vortex age.

Dunley, Jr., W. J. and Muldoon, J. P.

"EFFECT OF WAKE VORTEX INTERACTION ON DELAYS AT LAGUARDIA AIRPORT"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 28-1 - 28-11

One of the primary runway-use configurations at LaGuardia Airport (LGA) involves arrivals on Runway 22 and departures on Runway 31. The FAA requires a standard two-minute wake turbulence separation between a heavy jet departure on Runway 31 and an arrival on Runway 22. This wake-vortex interaction manifests itself mainly as large arrival delays, because controllers in the LGA Tower must ask the New York TRACON to create and maintain a 6 to 7 nautical mile gap between arrivals for each heavy jet departure. This interaction is one of the major causes of delays at LGA and is expected to worsen in the future with an expected increasing percentage of heavy jet aircraft in the mix.

Dupeyrat, M., Aubry, S., Hesselink, H., Loth, S., Remiro, A., Schmollgruber, P., Verbeck, R. and Welman, C.

"EVALUATION OF OPERATIONS ON AN AIRPORT WITH A CIRCULAR RUNWAY"

ICAS 2014, September 2014, St. Petersburg, Russia.

This paper presents an innovative concept for airport operations in the long-term future, based on a radically new airport design encompassing a circular circumventing runway. The Endless Runway project, mostly funded by the European Commission, during the Framework Programme 7, aims at evaluating the benefits and identifying the constraints associated to this kind of airport. The possibility to operate the airport whatever the wind direction and for every aircraft type, the optimization of air

and ground aircraft trajectories using the best runway section, as well as the compact airport footprint are part of the observed gains. Those must be balanced with the high runway construction cost, additional safety issues in gusty winds and the impossibility to extend the runway system if additional capacity is desired. A foreseen application could be a small airport dedicated to unmanned aircraft operations or a large hub airport with limited traffic mix and high reliability of operations.

Dupont, P., Croisier, G., Werquin, O. and Stanislas, M.

"DPIV, HPTV AND VISUALIZATION STUDY OF A VORTEX RING-MOVING WALL INTERACTION"

Experiments in Fluids, Vol. 33, 2002, pp. 555-56.

This paper presents an experimental study of the interaction between a vortex ring and a moving wall. This type of flow can be considered as modeling, in a simplified way, the interaction between a 'typical eddy' and the viscous sublayer of a turbulent boundary layer. In the present study, the vortex ring is considered as a three-dimensional (3D) perturbation of a viscous Stokes layer. The interaction was first characterized by visualization. To obtain quantitative information, digital particle image velocimetry (DPIV) and holographic particle-tracking velocimetry (HPTV) were used. These different techniques led to a precise and detailed characterization of the vortex ring alone and of an interaction in which a hairpin vortex is generated in the Stokes layer. The results obtained show a good similarity between the observed vortex ring and the Oseen model. They also validate the Stokes layer model and show that in the present conditions, the hairpin vorticity is comparable to that of the Stokes layer. The holographic study, which was undertaken to obtain full 3D three-component (3D3C) velocity maps, showed the present limitations of HPTV.

Duque, E. P. N., Stone, C. P., Hennes, C. C. and Gharakhani, A.

"A HYBRID VORTEX-PARTICLE METHOD FOR ROTORCRAFT APPLICATIONS"

AIAA Paper No. 2012-2912, June 2012, New Orleans, LA.

A rotor wake simulation method based upon the Lagrangian vortex particle method (VPM) has been coupled with the OVERFLOW-2 grid-based CFD code to accurately predict the vortex dynamics in the wake of rotorcraft. Computational benchmarks are presented demonstrating the efficiency of the GPU-based tree algorithm for the Biot-Savart velocity induction. Numerical simulation results are compared to experimental wind-tunnel measurements of a rotor-fuselage assembly demonstrating the fidelity and efficiency of the hybrid particle-grid simulation strategy.

Duque, E. P. N., Toyoda, A., Burklund, M. D. and Hariharan, N.

"STANDARDIZED POST-PROCESSING AND VISUALIZATION OF PARTICIPANTS' SIMULATIONS OF A ROTOR IN HOVER"

AIAA Paper 2017-1668, January 2017, Grapevine, TX.

For the AIAA Special Session for Rotors in Hover 2017 Computational Fluid Dynamics (CFD) simulations of two helicopter rotor in hover cases were studied -- the S-76 rotor and the proposed PSP rotor. Four participants uploaded their results to a remote 'cloud server' and then FieldView extract-based post-processing tools were used to automatically extract and present the resultant flow features such as tip vortices via velocity contours and iso-surfaces. This automated system enabled researchers to concentrate on understanding the flow physics and perform unbiased comparisons. The paper herein presents the results for four of the participants.

Duraisamy, K. and Baeder, J. D.

"NUMERICAL SIMULATION OF THE EFFECTS OF SPANWISE BLOWING ON WING-TIP VORTEX FORMATION AND EVOLUTION"

AIAA Paper No. 2005-4726, Toronto, Canada, June 2005

A high-resolution computational methodology is developed for the solution of the Compressible Reynolds Averaged Navier Stokes (RANS) equations. This methodology is used to study the formation and control of tip vortices from fixed wings. The numerical error is reduced by using high order accurate schemes on appropriately refined meshes. For vortex evolution problems, the equations are solved on multiple overset grids that ensure adequate resolution in an efficient manner. Reliable validations of the mean flow field are obtained by adding a simple correction to the production term in the Spalart-Allmaras turbulence model in order to account for the stabilizing effects of rotation in the core of the tip vortex. The fidelity of the approach allows for a detailed study of the underlying physics of vortex formation and evolution. The effect of spanwise blowing on the vortex structure is investigated with some experimental validation.

Duraisamy, K. and Baeder, J. D.

"NUMERICAL SIMULATION OF THE EFFECTS OF SPANWISE BLOWING ON TIP VORTEX FORMATION"

Journal of Aircraft, Vol. 43, No. 4, July-August 2006, pp. 996-1006

A high-resolution computational methodology is developed for the solution of the compressible Reynolds-averaged Navier-Stokes equations. This methodology is used to study the effect of spanwise blowing as a method of tip vortex control. The numerical error is reduced by using high order accurate schemes on appropriately refined meshes. For vortex evolution problems, the equations are solved on multiple overset grids that ensure adequate resolution in an efficient manner. Reliable validation of the mean flow field for the baseline and control configurations is obtained by adding a simple correction to the production term in the Spalart-Allmaras turbulence model. A detailed study of the underlying physics of the effects of spanwise blowing is presented.

Duraisamy, K. and Baeder, J. D.

"HIGH RESOLUTION WAKE CAPTURING METHODOLOGY FOR HOVERING ROTORS"

Journal of the American Helicopter Society, Vol. 52, No. 2, April 2007, pp. 110-122.

A high-resolution Reynolds-averaged Navier-Stokes (RANS) solver is applied to study the evolution of tip vortices from rotary blades. The numerical error is reduced by using high-order accurate schemes on appropriately refined meshes. To better resolve the vortex evolution, the equations were solved on multiple overset grids that ensured adequate resolution in an efficient manner. For the RANS closure, a one equation wall-based turbulence model was used with a correction to the production term to account for the stabilizing effects of rotation in the core of the tip vortex. While experimental comparison of the computed vortex structure beyond a few chord lengths downstream of the trailing edge is lacking in the literature, reasonable validation of the vortex velocity profiles is demonstrated up to a distance of 50 chord lengths of evolution for a single-bladed rotor. For the two-bladed rotor case, the tip vortex could be tracked up to two rotor revolutions with minimal diffusion. The accuracy of the computed blade pressures and vortex trajectories confirm that the inflow distribution and blade-vortex interaction are represented correctly. The accuracy achieved in the validation studies establishes the viability of the methodology as a reliable tool that can be used to predict vortex evolution and the aerodynamic performance of hovering rotors.

Duraisamy, K. and Lele, S. K.

"EVOLUTION OF ISOLATED TURBULENT TRAILING VORTICES"

Physics of Fluids, Vol. 20, 2008, pp. 035102-1 - 035102-11.

In this work, the temporal evolution of a low swirl-number turbulent Batchelor vortex is studied using pseudo-spectral direct numerical simulations. The solution of the governing equations in the vorticity-velocity form allows for accurate application of boundary conditions. The physics of the evolution is investigated with an emphasis on the mechanisms that influence the transport of axial and angular momentum. Excitation of normal mode instabilities gives rise to coherent large scale helical structures inside the vortical core. The radial growth of these helical structures and the action of axial shear and differential rotation results in the creation of a polarized vortex layer. This vortex layer evolves into a series of hairpin-shaped structures that subsequently breakdown into elongated fine scale vortices. Ultimately, the radially outward propagation of these structures results in the relaxation of the flow towards a stable high-swirl configuration. Two conserved quantities, based on the deviation from the laminar solution, are derived and these prove to be useful in characterizing the polarized vortex layer and enhancing the understanding of the transport process. The generation and evaluation of the Reynolds stresses is also addressed.

Duraisamy, K. and Lele, S. K.

"DNS OF TEMPORAL EVOLUTION OF ISOLATED TURBULENT VORTICES"

Proceedings of the Summer Program 2006, Center for Turbulence Research, pp. 35-47

The temporal evolution of isolated turbulent Batchelor vortices is investigated using pseudo-spectral direct numerical simulations (DNS) of the vorticity transport equations. Analytic treatment of the

velocity at the domain boundaries (Rennich et al. (1997)) effectively isolates the vortex. The flow dynamics is examined over a range of swirl numbers. (The swirl number is a measure of the ratio of the azimuthal and axial velocities). For the cases in which the mean flow is unstable to normal mode perturbations, helical instabilities are seen to grow and advect radially. The local stretching and tilting of vortex lines by these instabilities is seen to generate mean counter-signed axial vorticity, and consequently, a circulation overshoot. The velocity field introduced by the distorted vortex tries to concentrate the axial vorticity away from the centerline. For low swirl cases, the axial vorticity is briefly shifted almost entirely to helical lobes near the edge of the vortical core. Ultimately, the coherence of the helical structures is lost and the flow progresses toward equilibrium. Angular momentum transport to the exterior potential flow is seen to be enhanced by the radial advection of streamwise oriented vorticity. During the return to equilibrium, azimuthal vorticity is present in the exterior of the core in the form of highly stretched spirals. While there is very little turbulent mixing in the inner part of the core, the turbulent kinetic energy and dissipation are seen to peak at the core centerline.

Duraisamy, K., Ramasamy, M., Baeder, J. D. and Leishman, J. G.

"HIGH-RESOLUTION COMPUTATIONAL AND EXPERIMENTAL STUDY OF ROTARY-WING TIP VORTEX FORMATION"

AIAA Journal, Vol. 45, No. 11, November 2007, pp. 2593-2602

The formation and rollup of a tip vortex trailed from a hovering helicopter rotor blade is studied in detail using both computations and measurements. The compressible Reynolds-averaged Navier-Stokes equations are computationally solved on an overset mesh system. The flow measurements are made using stereoscopic particle image velocimetry. The high resolution of both the numerics and the measurements reveal multiple coherent structures in the evolving rotor tip vortex flow field. Secondary and tertiary vortices that result from crossflow separations near the blade tip are identified. These vortices, along with a part of the trailed wake, are ultimately entrained into the tip vortex that is formed downstream of the blade's trailing edge. The simulations clearly demonstrate the resolution required to accurately represent the complex three-dimensional flow field. The advantage of particle image velocimetry, which can make planar measurements at a given instant of time, has been fully used to validate the computational fluid dynamics predictions. Even though linear eddy viscosity models are expected to inadequately represent the details of the turbulent quantities, good agreement is seen to be achieved with the particle image velocimetry measurements of the mean flow field. The various sources of computational and measurement uncertainties are discussed.

Durgin, F. H., Pastrone, C. J. and Marenzi, O. B.

"COMPARISON OF MEASURED WIND VELOCITIES FROM THE TOP OF AN 800 FOOT TOWER IN BOSTON AND LOGAN AIRPORT BOSTON"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 36, 1990, pp. 403-413.

The existence of five years of wind speed and direction data from the top of a 100-foot tower mounted at the top of an 800-foot-tall building in Boston has been noted. Preliminary analysis of the data shows that the presence of the building affects both the indicated wind direction and speed. An initial calculation of the ratio of uncorrected fastest hourly wind speed each day at the tower to the fastest mile data measured at Logan Airport produced an average ratio of 1.50. That compares reasonably with the value of 1.52 normally used at the MIT Wright Brothers Facility, but much additional analysis is needed to confirm that result.

Durgin, W. W. and Karlsson, S. K. F.

"ON THE PHENOMENON OF VORTEX STREET BREAKDOWN"

J. Fluid Mech., Vol. 48, No. 3, August 1971, pp. 507-527

A von Karman vortex street generated in the usual way was subjected to a deceleration, thereby changing the ratio of longitudinal to lateral spacing between the vortices. Distortion of the individual vortices followed which resulted in annihilation of concentrated vortex regions and creation of a stationary wake flow. This wake flow was itself dynamically unstable and developed into a new vortex street of a different frequency from the initial one. The breakdown of the initial vortex street is qualitatively explained by considering the convection of a concentrated vortex region due to the motion imposed by all the other vortices. In ground effect, stratification also inhibits horizontal migration and cancels the rebound effect (observed in the non-stratified, non-sheared case). In a non-stratified flow with shear, vortex evolution is asymmetric, and, in ground effect, the shear also acts to severely reduce the rebound effect. With stratification and shear (Richardson number equal to one), the flow is asymmetric, and two effects are observed. When the vortex pair is weak relative to the shear (strong crosswind condition), the weaker downwind vortex is closer to the ground than the stronger upwind vortex. (If the vortex pair is far from the ground, a solitary vortex develops in this case.) If the vortex is stronger relative to the shear (weak crosswind conditions), the weaker downwind vortex is further from the ground than the stronger upwind vortex. In either case, the vortices may migrate far from their initial generation position.

Durston, D. A., Walker, S. M., Driver, D. M., Smith, S. C. and Savas, O.

"WAKE-VORTEX ALLEVIATION FLOWFIELD STUDIES"

Journal of Aircraft, Vol. 42, No. 4, July-August 2005, pp. 894-907

Wake-vortex-alleviation research was conducted in the far-field vortex wake of a generic wing-tail aircraft model. The goals were to achieve accelerated vortex strength reduction and to map the conditions at which this reduction would occur. The wing-tail model was run in a water tow tank to generate a pair of unequal-strength counter-rotating vortices on each side of centerline. Dye flow visualization provided physical insight into the nature of the vortex interactions, and three-component particle image velocimetry allowed quantification of key characteristics of the flow field, including circulation, vorticity, vortex trajectory, and induced rolling moments. Experiments were conducted for

a variety of model angles of attack, tail incidence angles, and tail spans. The results showed that with high tail/wing circulation ratios (high tail downloads) the tail and wing vortices interacted strongly, leaving substantially weakened vortices after a distance of about 60 to 70 spans downstream of the model. A longitudinal static stability analysis identified the moderate-to-high static margins required to achieve such circulation ratios.

Durston, D. A., Walker, S. M., Driver, D. M., Smith, S. C. and Savas, O.

"WAKE VORTEX ALLEVIATION FLOW FIELD STUDIES"

AIAA Paper No. 2004-1073, Reno, NV, January 2004

Wake vortex alleviation research was conducted in a water tow-tank investigation of the far-field wake from a generic wing-tail aircraft model. The goals of the research were to achieve accelerated vortex breakdown and to map the conditions - the relative vortex strengths and locations - for which this breakdown would occur. The wing-tail model was used to generate a pair of unequal-strength counter-rotating vortices on each side of centerline. Both qualitative and quantitative data were recorded from the model runs: dye flow visualization and particle-image velocimetry (PIV). The flow visualization provided physical insight into the nature of the vortex interactions, and the three-component PIV velocity measurements allowed calculation of key characteristics of the flow field, including circulation, vorticity, and other parameters. Data were obtained for a variety of model angles of attack, tail incidence angles, and tail spans. The results showed that with high tail/wing circulation ratios (high tail downloads), the tail and wing vortices interacted so as to leave very little recognizable vortex structure after a distance of about 60 to 70 spans downstream of the model. A longitudinal static stability analysis identified the moderate-to-high static margins required to achieve such circulation ratios.

Duwaldt, F. A.

"WAKES AND LIFTING PROPELLERS (ROTORS) IN GROUND EFFECT"

CAL-BB-1665-S-3, November 1966, Cornell Aeronautical Lab., Buffalo, NY

The report presents the development of a wake model for a lifting propeller (rotor) in ground effect and the computation procedure used to determine the special distribution of wake vorticity and the induced velocity field accompanying that vorticity distribution. Sample calculations for a two-bladed rotor were carried out. Locations of wake vortical elements and the associated induced velocities at selected field points are presented for various advance ratios for a H/R ratio of rotor height above ground to rotor radius of 1.0. A few results for a hovering case with $H/R = 0.5$ are presented. A calculated root-mean-square velocity map is compared with measured hovering data and good agreement is obtained in the outer half of the slipstream.

Dvorak, R.

"AERODYNAMICS OF BIRD FLIGHT"

EPJ Web of Conferences, Vol. 114, 2016, pp. 01001-1 to 01001-8.

Unlike airplanes birds must have either flapping or oscillating wings (the hummingbird). Only such wings can produce both lift and thrust -- two sine qua non attributes of flying. The bird wings have several possibilities how to obtain the same functions as airplane wings. All are realized by the system of flight feathers. Birds have also the capabilities of adjusting the shape of the wing according to what the immediate flight situation demands, as well as of responding almost immediately to conditions the flow environment dictates, such as wind gusts, object avoidance, target tracking, etc. In bird aerodynamics also the tail plays an important role. To fly, wings impart downward momentum to the surrounding air and obtain lift by reaction. How this is achieved under various flight situations (cruise flight, hovering, landing, etc.), and what the role is of the wing-generated vortices in producing lift and thrust is discussed. The issue of studying bird flight experimentally from in vivo or in vitro experiments is also briefly discussed.

Dyachevsky, A. P., Glushkov, N. N. and Kozachenko, A. V.

"TRANSFORMATION OF EXTERNAL DISTURBANCES BY THE WING VORTEX SYSTEMS OF AN AIRCRAFT FLYING THROUGH A NON-UNIFORM MEDIUM"

In: Flight Safety, Aircraft Wake Vortex and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 223-225

The problem on computing the aerodynamic effect of the vortex wake generated by an aircraft on other aircraft at low subsonic speeds is considered in the linear formulation. The velocity field of an arbitrary structure is shown to be transformed by free vortices into a field uniform in chordwise direction and varying in the spanwise direction. The field thus transformed is perceived by the wing bound vortices which induce corresponding aerodynamic loads. The transformation of the non-uniform velocity field to the uniform one by the free vortices is the primary reason why the solution in quasi-steady approximation differs from that of the unsteady problem.

Dyachevsky, A. P., Glushkov, N. N. and Mikhailov, Y. S.

"MODIFICATION OF A PANEL METHOD FOR CALCULATION OF THE AIRCRAFT AERODYNAMIC LOADING UNDER VORTEX WAKE ENVIRONMENT"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 214-222

In the framework of the hypothesis of a 'frozen' external velocity field, a panel method is modified for calculation of the vortex wake effect on the aircraft flying along a path close to the centerline of one of the wake vortices generated by a leading aircraft. The non-symmetry inherent in the nonuniform velocity field around the aircraft components is considered by representing the fuselage geometry with wing panels and introducing additional information about the velocity field in the control points of the

aircraft surface. The verification of the numerical method against the results of testing the aircraft model in the nonuniform wind tunnel flow has shown a satisfactory accuracy of prediction of aerodynamic characteristics over a range of linear variations of the wing lifting capacity.

Dynnikov, A. A.

"DEVELOPMENT OF VORTEX WAKE INSTABILITY UNDER THE ACTION OF ATMOSPHERIC TURBULENCE"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 119-128

The sinuous instability known as Crow's instability is one of substantial factors influencing the vortex decay behind an aircraft. It is usually assumed that the vortex wake can be considered as destroyed when the amplitude of vortex core deviations from their initial positions becomes equal to the initial distance between them. It is evident that these deviations vary as some random process whose parameter distributions were the subjects of this study. Air turbulence was assumed to be the source of disturbances provoking the development of Crow's instability. On this assumption, in this work the expression for the spectral density function of vortex deviations has been obtained and various turbulence models have been compared. The results obtained can be used both for calculating the probability of vortex to decay at a time specified as well as for statistical simulation purposes. [In Russian.]

Dynnikov, A. A.

"THE INFLUENCE OF ATMOSPHERIC TURBULENCE ON CROW INSTABILITY INITIATION"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

The sinusoidal instability known as the Crow instability is an essential factor affecting the disintegration of the vortex wakes. This instability should be considered in the wake vortex decay model intended for the investigation of the second airplane dynamics. The initiation of the Crow instability due to atmospheric turbulence and variable wing loads is considered in some publications in which the lifespan of a vortex time is estimated. In this investigation it is supported that the wake vortices disappear when the amplitude of vortex line deviations from an initial position becomes equal to the initial distance between them. There are several experimental works in which the vortex lifespan is estimated at different turbulence levels. To investigate the second airplane dynamics, it is necessary to know not only the lifespan of a trace, but also a spatial position of vortex lines. This position is a random process, the characteristics of which depend on many factors, mainly on atmospheric turbulence. The purpose of this paper is to determine the characteristics of this process. These characteristics can be used to construct an algorithm which generates random realizations of the wake vortex position in space. Such an algorithm can be used for the investigation of the second airplane dynamics.

Dynnikova, G. Ya.

"VORTEX MOTION IN TWO-DIMENSIONAL VISCOUS FLUID FLOWS"

Fluid Dynamics, Vol. 38, No. 5, 2003, pp. 670-678

The diffusion and annihilation of vortices in axisymmetric and plane incompressible viscous fluid flows are considered. A formula relating the pressure with the velocity of the vortices in the viscous fluid is obtained.

Dziedzic, M. and Leutheusser, H. J.

"AN EXPERIMENTAL STUDY OF VISCOUS VORTEX RINGS"

Experiments in Fluids, Vol. 21, 1996, pp. 315-324

The work focuses on the problem of stability and viscous decay of single vortex rings. A tentative classification scheme is proposed for vortex rings which is based on extensive hot-wire measurements of velocity in the ring core and wake, and flow visualization, viz. laminar, wavy, turbulence-producing, and turbulent. Prediction of vortex ring type is shown to be possible, at least approximately, based on the vortex ring Reynolds number alone. Linear growth rates of ring diameter with time are observed for all types of vortex rings, with different growth rates occurring for laminar and turbulent vortex rings. Data on the viscous decay of vortex rings are used to provide experimental confirmation of the accuracy of Saffman's equation for the velocity of propagation of a vortex ring.

Early, J. M. and Green, R. B.

"PHENOMENA OBSERVED DURING THE ORTHOGONAL BLADE-VORTEX INTERACTION"

4th International Symposium on Particle Image Velocimetry, Paper 1180, September 2001, Gottingen, Germany.

Through the application of a Particle Image Velocimetry (PIV) technique, the flow field associated with the Orthogonal Blade-Vortex Interaction (BVI) has been examined. The use of the PIV technique has allowed quantitative measurement of the orthogonal BVI to be carried out, examining in detail the progression of the interacting vortex from the leading edge to the trailing edge region of the blade, and the effect of the interaction on the vortex core axial flow. The PIV system has also been successfully utilized in conjunction with a pressure data acquisition system, allowing simultaneous pressure data capture and analysis of the position of the interacting vortex in relation to the pressure transducers. This paper will outline the experimental techniques employed, and highlight the salient features observed within this investigation.

Earnshaw, P. B.

"PRELIMINARY RESULTS USING A RAPID PHOTOGRAPHIC WAKE TRAVERSE SYSTEM"

RAE-TM-AERO-1987, November 1983, Royal Aircraft Establishment, Farnborough, England

A rapid photographic wake traverse system was constructed for a 4 ft x 3 ft wind tunnel to assess the feasibility of, and design requirements for, a similar equipment to suit a 5 m wind tunnel. Sample photographs using a gothic wing and a Harrier model with and without stores show the ease with which useful information can be acquired.

Earnshaw, P. B.

"MEASUREMENTS OF VORTEX-BREAKDOWN POSITION AT LOW SPEED ON A SERIES OF SHARP-EDGED SYMMETRICAL MODELS"

ARC Paper CP-828, November 1964, Royal Aircraft Establishment, Farnborough, England

Measurements have been made at low speed of vortex-breakdown positions on a series of five, symmetrical wings, using a schlieren system to detect the position of breakdown. The results suggest that the modification of a delta planform to incorporate streamwise tips has little effect on breakdown position when this is forward of the modified tip. Examination of the large differences between these measurements and those from other sources suggests that the influence of cross-sectional shape even on nominally thin wings may be larger than expected and merits further investigation.

Easterbrook, C. C. and Joss, W. W.

"THE UTILITY OF DOPPLER RADAR IN THE STUDY OF AIRCRAFT WING-TIP VORTICES"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 97-112

The feasibility of utilizing a special purpose Doppler radar to investigate air motions in aircraft wakes is explored and tested. One method involves the injection of radar reflecting chaff into the wing-tip vortex of an aircraft in flight, and subsequently recording the Doppler spectrum of the return from the chaff packet as obtained by the radar looking normal to the flight path. The second method consists of Doppler measurements in the wake behind aircraft on the approach to an airport during snow conditions, where natural snow crystals and flakes assume the role of radar reflecting tracers of air motion. The power spectra derived from both techniques reflect the distribution of velocities of scatterers in the direction of the radar, weighted by the spatial distribution of the scatterers contained in the radar sensitive volume.

Easterbrook, C. C., Joss, W. W. and Prinsen, H. W.

"AN EXPERIMENTAL INVESTIGATION AND EVALUATION OF A DOPPLER RADAR TECHNIQUE FOR THE MEASUREMENT OF THE FLOW GENERATED BY WING TIP VORTICES"

CAL-AF-3015-1, January 1971, Cornell Aeronautical Lab., Buffalo, NY

Results are described of tests conducted to determine if radar reflective chaff injected at the wing tip of an aircraft would be ingested into the vortex structure and sufficiently distributed to allow velocity profiles to be measured by a Doppler radar. The results are presented in the form of flow field visualization results and an analysis of radar returns. The data show that individual chaff filaments dispensed at the wing tips of an Aztec aircraft are entrained by the wing tip vortices. An examination of the radar returns reveals the presence of large Doppler spreads in relatively small regions of the vortices. It was also found that a substantial percentage of the chaff tended to form clumps which hampered the determination of the detailed velocity profiles.

Eaton, J. A. and O'Flaherty, M. P.

"FLOWFIELD PREDICTION OF THREE-DIMENSIONAL WING TRAILING VORTICES USING ADVANCED TURBULENCE MODELS, "

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 7-1 to 7-.

The feasibility of employing a general-purpose Navier-Stokes code, in conjunction with a Reynolds stress transport turbulence model, for predicting wake vortex flow fields is investigated. Two test cases are considered, each employing two different turbulence models, a model, which is isotropic, and an anisotropic, differential Reynolds stress model. First the flow field around a low aspect ratio wing in a wind tunnel is computed to assess the influence of the turbulence model on the solution. Pressure distributions on the surface and velocity distributions in the wake, particularly the streamwise component, are compared with measurements. Although the grids used are suboptimal, predictions indicate a qualitative improvement for the anisotropic model, in particular where the swirl component of the flow is greater, such as in the vortex core. Next, wind tunnel data are used as a starting point for an axisymmetric model of a free vortex with axial flow. These computations allow the effects of choice of turbulence model on the aging and decay of a vortex in the far field to be observed. The k-epsilon model predicts a rapid growth of the vortex, whereas the differential Reynolds stress model results in a more realistic, almost uniform evolution of the core radius.

Eaton, J. K. and Matalanis, C.

"TRANSLATING ACTIVE GURNEY FLAP TO ALLEVIATE AIRCRAFT WAKE VORTEX HAZARD"

US Patent Application 2009/0321582 A1, December 2009.

A wake vortex alleviator is provided. The wake vortex alleviator produces rapid variations in the position of vortices emanating from aerodynamic surfaces by using an active flap that moves span-wise back and forth along the outboard section of the surface. Rapidly moving the flap back and forth in a slot at an appropriate frequency will cause the vortex to oscillate, resulting in interaction between other vortices and subsequent destruction much earlier than it would occur naturally. The slot is positioned near the aerodynamic surface trailing edge and generally transverse to a chord line of the aerodynamic surface. The flap can be moved using a variety of actuators to position, translate and stow

the flap. The oscillation frequency and position are guided by information feedback according variations in lift in the aerodynamic surface, such as wind gusts. The flaps can control yaw, roll and pitch of the aerodynamic surface.

Eberle, W. R.

"PILOT RESPONSE TO WAKE TURBULENCE ENCOUNTERS AT NEW YORK'S LAGUARDIA AIRPORT"

LMSC-HSV TR-P038105, October 1993, Lockheed Missiles & Space Corp., Huntsville, AL

This effort was initiated to develop a rationale for decreasing the aircraft spacing required for vortex consideration at LaGuardia Airport in New York. During the winter months, the primary runway configuration is takeoff on Runway 31 and landing on Runway 22. FAA procedures require an increase in the distance a landing aircraft must be from the runway intersection when a heavy takeoff aircraft crosses the intersection. The extra distance is required to permit demise of the vortices from the heavy takeoff aircraft before the next aircraft lands on Runway 22. This report examined normal pilot response to cross-vortex encounters to see if such response would create a hazardous condition. B-727 and DHC-7 simulators were used. Pilots reported that any cross-vortex encounters could be handled safely with training and warning of a heavy aircraft takeoff; the encounter could be dangerous if it were conducted without training and/or warning.

Eberle, W. R. and Dillard, A. E.

"WAKE VORTEX PROGRAM FOR CROSS-VORTEX ENCOUNTERS AT LAGUARDIA AIRPORT"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 54-1 - 54-28

One of the primary runway configurations for LaGuardia Airport is departure on Runway 31 and landing on Runway 22. Because of wake vortex considerations, the FAA enforces the standard 3/4/5/6 n.mi. vortex separations between a heavy aircraft departing on Runway 31 and a landing aircraft on Runway 22. When aircraft separations are established by IFR control, if a heavy take-off aircraft on Runway 31 crosses the intersection, any large aircraft landing on Runway 22 must be five miles from the intersection. The capacity of LaGuardia Airport is significantly degraded by this spacing requirement. A study was initiated to determine if a rationale for eliminating the additional spacing imposed by wake vortex considerations of Runway 31 aircraft could be developed. If such a rationale were developed, aircraft performing IFR landings on Runway 22 would maintain normal separations for landing aircraft without consideration of the type of aircraft departing on Runway 31. The initial approach to developing such a rationale was to analyze vortex transport and demise to determine if vortex encounters could be avoided. The initial study showed that vortex encounters would be very rare, but could not be completely avoided. The second approach was to demonstrate that aircraft response to a cross-encounter is significantly different from aircraft response to an in-trail encounter and to demonstrate that a cross-vortex encounter is innocuous for transport category aircraft.

Eberle, W. R., Brashears, M. R., Zalay, A. D., Shrider, K. R. and Love, D. A.

"AIRCRAFT WAKE VORTEX CHARACTERISTICS FROM DATA MEASURED AT JOHN F. KENNEDY INTERNATIONAL AIRPORT"

FAA-RD-78-47, March 1978, Lockheed Missiles & Space Co., Huntsville, AL

Data from 1320 aircraft flybys at Kennedy International Airport, Jamaica, New York, in 1975 were processed and stored in a computerized vortex data management system. The data were selectively recalled to determine vortex characteristics pertinent to the design of an effective wake vortex avoidance system. Vortex and meteorological characteristics which are relevant to the design of an effective wake vortex avoidance system are discussed from an analytical viewpoint as well as from an analysis of the data. Several formulations for feedback of vortex sensor information to provide vortex prediction are presented. Several wake vortex avoidance system designs are shown.

Eberle, W. R., McCutcheon, W. A. and Shrider, K. R.

"WAKE TURBULENCE INVESTIGATION AT NEW YORK'S LA GUARDIA AIRPORT"

LMSC-HEC TR F225747-B, December 1988, Lockheed Missiles & Space Co., Huntsville, AL

The intent of the study was the development of a rationale for increased airport capacity by eliminating the extra space required for aircraft landing behind heavy takeoff aircraft at La Guardia airport. The study considered two approaches: (1) demonstration that a vortex encounter would not occur for the runway configuration of interest (takeoff on runway 31 and landing on runway 22), and (2) demonstration that if a vortex encounter occurred where the flight path of the following aircraft is perpendicular to the flight path of the generating aircraft, it would not be hazardous to the landing aircraft.

Echavez, G. and McCann, E.

"AN EXPERIMENTAL STUDY ON THE FREE SURFACE VERTICAL VORTEX"

Experiments in Fluids, Vol. 33, 2002, pp. 414-421

An experimental investigation of the three-dimensional configuration of a vertical vortex flow, showing the importance of separating the radial and axial components of the total outflow, is presented. The relative magnitudes of the axial and radial flow components are measured and the depth of the air core is shown to be highly sensitive to the axial flow component. A representation of the flow in the core zone is also presented which may indicate internal boundary conditions that may be of interest to those developing theoretical models.

Economou, T.

"EFFECTS OF WAKE VORTICES ON COMMERCIAL AIRCRAFT"

The strength of a wake vortex can be modeled and quantified by the coefficient of roll which a penetrating aircraft will experience when passing through a vortex. In this study, the coefficient was computed by a closed-form method and by using strip theory to analyze the effects of the vortex on the penetrating aircraft and determine the risk involved. Results showed that a penetrating aircraft with an equivalent span to the wake generating aircraft will experience a much lower coefficient of roll than when the penetrating aircraft has a smaller span. Further, the coefficient of roll induced by a trailing vortex with a small core radius will be stronger than that of a vortex with a larger radius. In all cases, at least one scenario existed where the penetrating aircraft could not produce a control power coefficient of roll of the same magnitude as the induced coefficient from the vortex. Also, the taper ratio of the penetrating wing affects the strength of the induced coefficient of roll. A more rectangular wing will experience a stronger induced roll coefficient than a wing with taper. Lastly, the effect of the spanwise vortex location of the vortex on the penetrating wing was examined. The induced roll coefficient was found to be the largest when the aircraft penetrates along the vortex axis and the vortex axis coincides with the centerline of the airplane.

Edstrand, A. M., Schmid, P. J., Taira, K. and Cattafesta III, L. N.

"A PARALLEL STABILITY ANALYSIS OF A TRAILING VORTEX WAKE"

Journal of Fluid Mechanics, Vol. 837, 2018, pp. 858-895.

Trailing vortices are generated in aeronautical and maritime applications and produce a variety of adverse effects that remain difficult to control. A stability analysis can direct flow control designers towards pertinent frequencies, wavelengths and locations that may lead to the excitation of instabilities, resulting in the eventual breakup of the vortex. Most models for trailing vortices, however, are far-field models, making implementation of the findings from stability analyses challenging. As such, we perform a stability analysis in the formative region where the numerically computed base flow contains both a two-dimensional wake and a tip vortex generated from a NACA0012 at a 5- degree angle of attack and a chord-based Reynolds number of $Re=1000$. The parallel temporal and spatial analyses show that at three chord lengths downstream of the trailing edge, seven unstable modes are present: three stemming from the temporal analysis and four arising in the spatial analysis. The three temporal instabilities are analogues to three unstable modes in the spatial analysis, with the wake instability dominating in both analyses. The helical mode localized to the vortex co-rotates with the base flow, which is converse with the counter-rotating $m=-1$ instabilities of a Batchelor vortex model, which may be a result of the formative nature of the base-flow vortex. The fourth spatial mode is localized to the tip vortex region. The continuous part of the spectrum contains oscillatory and wavepacket solutions prompting the utilization of a wavepacket analysis to analyze the flow field and group velocity. The structure and details of the full bi-global spectrum will help navigate the design space of effective control strategies to hasten decay of persistent wingtip vortices.

Edwards, B. B. and Coffey, E. W.

"DEVELOPMENT AND TESTING OF LASER DOPPLER SYSTEM COMPONENTS FOR WAKE VORTEX MONITORING; VOL. 2: SCANNER OPERATIONS MANUAL"

NASA CR-120467, August 1974, Lockheed Missiles & Space Company, Huntsville, AL

This manual describes the theory and operation of the scanner portion of the Laser Doppler system for detecting and monitoring aircraft trailing vortices in an airport environment. Included in the manual are schematics, wiring diagrams, component values, and operation and check out procedures.

Eftekari, R. R., Hammer, J. B., Havens, D. A. and Mundra, A. D.

"FEASIBILITY ANALYSES FOR PAIRED APPROACH PROCEDURES FOR CLOSELY SPACED PARALLEL RUNWAYS"

Integrated Communications, Navigation and Surveillance (ICNS) Conference, May 2011, Herndon, VA.

In current air traffic operations in the U.S., closely spaced parallel runways (CSPRs) separated by less than 2500 feet can be used to conduct simultaneous parallel operations using visual separation. Once below visual approach minima, such dual runway operations are no longer possible. To address this loss of throughput, several concepts are currently under consideration. This paper discusses a 'paired approach' concept which enables use of CSPRs down to Category I and II approach minima. The paper documents Monte Carlo analyses on the feasibility and trade-offs of paired approach procedure variants with and without an escape maneuver. It concludes that both procedure variations require echelon staggering for most airports with runway centerline separations below 2500 ft and provides window parameters required for an acceptable Target Level of Safety. It shows that a value of up to 4000 ft for this echelon spacing is adequate for most CSPRs for an adverse wind threshold of 10 knots; the specific value depending on the concept variation and geometry. Other findings include the ability to achieve abeam positioning with an escape procedure for several runway configurations. Many procedural combinations examined are capable of pairing 95 to 100 percent of aircraft. Additionally, this paper presents an analysis of wake encounter risk during blunders. The analysis results suggest the non-escape procedure variant has a high probability of wake vortex encounter during blunder. On the other hand, the escape procedure variant with a delay in breakout of 8 seconds or less appears to provide protection from wake encounters even during a blunder.

Egolf, T. A.

"AN ANALYTICAL AND EXPERIMENTAL STUDY OF FARFIELD ROTOR WAKE GEOMETRY AND VELOCITY"

MS Thesis, August 1973, Pennsylvania State University, University Park, PA.

All fixed wing aircraft generate trailing vortex wakes whose circulatory strength is dependent on flight conditions and aircraft geometry. A rotor also generates a vortex wake. A vortex sheet is shed from each blade. Each sheet rolls up rapidly outboard to form a tip vortex. The purpose of the study here is to estimate the rotor wake geometry and velocity field downstream of the rotor for the particular case where the rotor wake exhibits strong similarities to the fixed wing wake. A method is developed by

which the helicopter far field wake can be readily compared to the far field wake generated by an equivalent wing.

Egolf, T. A.

"AN ANALYTICAL AND EXPERIMENTAL STUDY OF FARFIELD ROTOR WAKE GEOMETRY AND VELOCITY"

PSU Aersp. 73-7, August 1973, Pennsylvania State Univ., University Park, PA

From the analyses and empirical measurements performed in this study, it appears that the far field wake of a rotor can be adequately described by treating the rotor as a circular wing.

Egolf, T. A. and Landgrebe, A. J.

"GENERALIZED WAKE GEOMETRY FOR A HELICOPTER ROTOR IN FORWARD FLIGHT AND EFFECT OF WAKE DEFORMATION ON AIRLOADS"

40th Annual Forum of the American Helicopter Society, May 1984, Arlington, VA.

An analytical investigation was conducted to develop a first level generalization of the predicted distorted wake geometry of a helicopter rotor in level steady forward flight and to demonstrate the influence of wake deformation on the prediction of rotor airloads. Distortions of the tip vortex relative to the classical undistorted geometry are generalized in terms of vortex age, blade azimuth, advance ratio, thrust coefficient, and number of blades for a representative rotor. A computer module and charts were developed for approximating wake geometry and identifying wake boundaries and locations of blade-vortex passage. Predicted H-34 airloads for several inflow/wake models are compared with data for selected flight conditions. The occurrence of close blade-vortex passages and the high sensitivity of predicted airloads to small deviations of blade to tip vortex distance demonstrate the requirement for improved blade-vortex interaction models. The airload correlations indicate that refined distorted wake methodology has the potential to provide more accurate airload prediction.

Egolf, T. A. and Landgrebe, A. J.

"HELICOPTER ROTOR WAKE GEOMETRY AND ITS INFLUENCE IN FORWARD FLIGHT. VOLUME 1: GENERALIZED WAKE GEOMETRY AND WAKE EFFECT ON ROTOR AIRLOADS AND PERFORMANCE"

NASA/CR-3726, October 1983, United Technologies Research Center, East Hartford, CT

An analytic investigation to generalize wake geometry of a helicopter rotor in steady level forward flight and to demonstrate the influence of wake deformation in the prediction of rotor airloads and performance is described. Volume 1 presents a first level generalized wake model based on theoretically predicted tip vortex geometries for a selected representative blade design. The tip vortex distortions are generalized in equation form as displacements from the classical undistorted tip vortex geometry in terms of vortex age, blade azimuth, rotor advance ratio, thrust coefficient, and number of blades. These equations were programmed to provide distorted wake coordinates at very low cost for

use in rotor airflow and airloads prediction analyses. The sensitivity of predicted rotor airloads, performance, and blade bending moments to the modeling of the tip vortex distortion are demonstrated for low to moderately high advance ratios for a representative rotor and the H-34 rotor. Comparisons with H-34 rotor test data demonstrate the effects of the classical, predicted distorted, and the newly developed generalized wake models on airloads and blade bending moments. Use of distorted wake models results in the occurrence of numerous blade-vortex interactions on the forward and lateral sides of the rotor disk. The significance of these interactions is related to the number and degree of proximity to the blades of the tip vortices. The correlation obtained with the distorted wake models (generalized and predicted) is encouraging.

Egolf, T. A., Bagai, A. and Tuozzo, N.

"OVERVIEW AND PERSPECTIVES OF VORTEX ELEMENT WAKE MODELING AT SIKORSKY"

Proceedings of the ARO Rotorcraft Wake Prediction Basic Research Workshop, March 2009, Georgia Institute of Technology, Atlanta, GA, pp. 4-29.

This paper presents several Sikorsky engineer's perspective on vortex- element based wake modeling for rotors, including a final emphasis on hybrid CFD/Vortex Element methodology. It briefly reviews some basic aspects of these models, their strengths and weaknesses, modeling issues, and what is needed to improve current hybrid CFD/Vortex Element methodology to support the aerodynamic design and analysis of isolated rotors. It directly or indirectly provides some insight into future research areas for this type of rotor wake modeling.

Egolf, T. A., Wake, B. E. and Berezin, C.

"RECENT ROTOR WAKE SIMULATION AND MODELING STUDIES AT UNITED TECHNOLOGIES CORPORATION"

AIAA Paper No. 2000-0115, Reno, NV, January 2000

The accurate prediction of the rotor wake and its influence on the rotorcraft continues to be a major obstacle for the rotorcraft community. Traditional vortex lattice methods are very useful, but cannot predict the details of the tip vortex formation. They are relatively efficient for tip vortex convection calculations, but are very sensitive to modeling assumptions. Traditional Computational Fluid Dynamics (CFD) applied to problems requiring accurate tip vortex convection is still too time consuming, primarily because of the very fine grid resolution required to avoid significant numerical diffusion. This paper is a summary of recent unpublished work at United Technologies Corporation (UTC) by engineers at Sikorsky Aircraft (SA) and United Technologies Research Center (UTRC) to improve the modeling assumptions and resolve some of the limitations of both vortex lattice and CFD methods. Two areas are addressed: tip vortex roll-up modeling in vortex lattice methods and ways to improve the calculation of the convection of the tip vortex in traditional CFD codes.

Ehert, T.

"STABILITY THEORY FOR TWO WINGTIP VORTICES BEHIND CRUISING AIRCRAFT"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 20-1 to 20-9

To perform a stability analysis on an interesting flow field, an undisturbed quasi steady basic velocity profile of the concerned flow field must be provided. In case of wake vortices behind cruising aircraft, the velocity distribution within the vortices must be evaluated as a function of the height coordinate z and the spanwise coordinate y . A three-dimensional vortex filament method was used to calculate the velocity field of the wake flow, because it is an efficient tool for flows consisting of large regions of vorticity. Vortex filament methods simulate such a flow field by discretizing the regions behind the aircraft wing which contain vorticity, and tracking this discretization in a Lagrangian reference frame. The velocity field behind the aircraft is determined kinematically from the given vorticity field and computed by an application of the Biot-Savart-law. Small perturbations are then superimposed on the given quasi steady base flow and this sum is then substituted into the governing equations. After a linearization process, two fourth order perturbation differential equations are found. They give rise to an eigenvalue problem with a complex eigenvalue w and eigenfunctions for the amplitudes of the disturbances.

Ehlers, J. and Fezens, N.

"AIRBORNE DOPPLER LIDAR SENSOR PARAMETER ANALYSIS FOR WAKE VORTEX IMPACT ALLEVIATION PURPOSES"

Advances in Aerospace Guidance, Navigation and Control, edited by J. Bordeneuve-Guibe, A. Drouin and C. Ross, Springer International Publishing, Switzerland, 2015, pp. 433-453.

This paper presents a sensitivity study of a wake vortex impact alleviation system based on an airborne forward-looking Doppler LiDAR sensor. The basic principle of the system is to use this sensor to measure the wind remotely ahead of the aircraft. Based on these measurements the system estimates whether a wake vortex is in front of the aircraft. If this is the case, the wake vortex characteristics are identified and the control deflections countervailing the wake-induced aircraft response are computed and applied. An integrated simulation environment comprising a full nonlinear 6-DoF A320 model (with control laws), wake vortex models, and the wake impact alleviation algorithms was developed. The LiDAR sensor subsystem has many design parameters that influence the overall performance in a complex way, which makes it difficult to derive adequate requirements. The presented parameter study provides first insights into the role of each parameter as well as some adequate parameter combinations.

Ehlers, J., Fischenberg, D. and Niedermeier, D.

"WAKE IMPACT ALLEVIATION CONTROL BASED ON WAKE IDENTIFICATION"

Journal of Aircraft, Vol. 52, No. 6, November-December 2015, pp. 2077-2089.

During a wake vortex encounter, an aircraft can experience significant attitude and flight-path changes, which can represent a severe safety risk. The application of a wake impact alleviation control system can considerably decrease the aircraft's response during the wake encounter and hence diminish the pilot workload while reducing the potential risk to the passengers, crew, and aircraft. The realization of a wake impact alleviation controller presented here is based on a forward-looking light detection and ranging (LIDAR) sensor. The information about the disturbance velocities in front of the aircraft is used to determine the control-surface deflections that compensate the wake-induced disturbance moments. The novel approach of this concept is the combination of the wake impact alleviation system with a wake identification algorithm. Because of the integration of the identification algorithm, it is possible to apply the wake impact alleviation with LIDAR sensors restricted to line-of-sight measurements only. The wake-identification-based wake impact alleviation is assessed in numerical aircraft simulations for different encounter scenarios, and a sensitivity study is performed for the parameters of the wake identification. It is shown that the alleviation system significantly reduces the wake-induced attitude change of the aircraft and thus represents a promising concept to increase safety during wake-vortex encounters.

Ehlers, J., Fischenberg, D. and Niedermeier, D.

"WAKE IDENTIFICATION BASED WAKE IMPACT ALLEVIATION CONTROL"

AIAA Paper 2014-2591, June 2014, Atlanta, GA.

During a wake vortex encounter an aircraft is exposed to strong unsteady disturbance velocities which can lead to significant changes in the aircraft attitude and flight path. This can present a severe safety risk and can result in injuries to the passengers and crew as well as damages to the aircraft. The application of a wake impact alleviation control system can considerably decrease the aircraft's response during the wake encounter, and hence diminish the pilot workload while reducing the potential risk to the passengers, crew, and aircraft. The realization of a wake impact alleviation controller presented here is based on a forward-looking LiDAR sensor. The information about the disturbance velocities in front of the aircraft is used to determine the control surface deflections that compensate the wake-induced disturbance moments. The novel approach of this concept is the combination of the wake impact alleviation system with a wake identification algorithm. Due to the integration of the identification algorithm, it is possible to apply the wake impact alleviation with LiDAR sensors restricted to line-of-sight measurements only. In this case the LiDAR sensor only detects the flow velocity in the direction of the measurement beam. A measurement of the full velocity vector of the flow field upstream of the aircraft, which LiDAR sensors of the foreseeable future will most likely be unable to provide, is not necessary for this approach. The wake identification-based wake impact alleviation is assessed for different encounter scenarios and a brief sensitivity study is performed for the most important parameters of the wake identification. It is shown that the wake impact alleviation control system significantly reduces the wake-induced attitude change of the aircraft and thus represents a promising concept to increase safety during wake vortex encounters.

Ehrenstein, U. and Le Dizes, S.

"RELATIONSHIP BETWEEN COROTATING VORTEX-PAIR EQUILIBRIA AND A SINGLE VORTEX IN AN EXTERNAL DEFORMATION FIELD"

Physics of Fluids, Vol. 17, No. 7, July 2005, 074103-1-074103-7

Two-dimensional corotating vortex pairs are computed as equilibrium solutions of the Euler equations and the influence of one vortex on the other is characterized in terms of a deformation field acting on an isolated vortex region. It is shown, by computing equilibrium states for a single vortex within an equivalent strain field, that the external rotating strain accounts for the elliptic deformation of the streamlines near the center of each vortex. Critical states, as a function of the strain rate, are reached when stagnation points start to penetrate the vortex regions at the outer boundary. While critical states for a single vortex within a uniform external rotating strain field consist of elliptical corner solutions, the vortex shapes lose the elliptical symmetry in the corotating case. We show that these asymmetric equilibrium states can be captured by a single vortex model if we consider higher order terms in the deformation field. We also demonstrate that the critical strain rates are of the same order of magnitude for both the single-vortex model and the interacting vortex pair.

Ehrenstein, U. and Rossi, M.

"COMPUTATION OF EQUILIBRIA BETWEEN TWO COROTATING NONUNIFORM VORTICES"

Lecture Notes in Physics, Issue 555, 2000, pp. 147-153

Understanding decaying two-dimensional turbulence has important consequences for geophysics, meteorology, and astrophysics. Various aspects appear in a recurrent way: from an initially unorganized two-dimensional flow, vorticity rapidly concentrates in localized regions called coherent structures and in vorticity filaments. In this framework, the computation of a nonlinear equilibrium between the vortices and its stability becomes an essential ingredient. Focusing on vorticity patches, equilibria of two unequal-area vortices have been computed for instance by Dritschel. However, vortices of two-dimensional turbulence are not vorticity patches. Our purpose is thus to verify how previous results obtained in the context of uniform vorticity are modified when nonuniform vortex pairs are considered.

Ehret, T. and Oertel, Jr., H.

"CALCULATION OF WAKE VORTEX STRUCTURES IN THE NEAR-FIELD WAKE BEHIND CRUISING AIRCRAFT"

Atmospheric Environment, Vol. 32, No. 18, September 1998, pp. 3089-3095

Wake flows behind cruising aircraft influence the distribution of the exhaust gases. A three-dimensional vortex filament method was developed to calculate the vortex structures and the velocity field of the vorticity dominated wake flows as an integration of the Biot-Savart law. For three-dimensional vortex filament calculations, self-induction singularities were prevented using a finite vortex core for each vortex filament. Numerical simulations show the vortex structures and the

velocity field in the wake behind a cruising Boeing 747 because of the integration of the Biot-Savart law. It is further shown how the structures of the fully rolled-up trailing vortices depend on the wing span loading, i.e. the circulation distribution.

Ehret, T. and Oertel, Jr., H.

"NUMERICAL SIMULATION OF THE DYNAMICS AND DECAY OF TRAILING VORTICES INCLUDING POLLUTANTS FROM AIR TRAFFIC"

In: Impact of Emissions from Aircraft and Spacecraft Upon the Atmosphere, Proceedings of International Scientific Colloquium, Cologne, Germany, 1992, pp. 268-273

Recent results from numerical simulations concerning the wake of an aircraft, including the pollutants, are presented. The computation of the rolling up of the trailing vortices and their effect on the jet emissions was performed using a 3D vortex filament method. Furthermore, a velocity profile of the trailing vortex, which serves as the starting point for a primary stability theory, is shown and the perturbation differential equations describing the vortex decay are derived.

Eisenhuth, J. J., McCormick, B. W., Nelson, R. C. and Garodz, L. J.

"ANALYSIS OF EXPERIMENTAL MEASUREMENTS OF TRAILING VORTEX SYSTEMS OF LARGE JET TRANSPORT AIRCRAFT"

Proceedings of the National Aerospace Electronics Conf., IEEE, 1971, pp. 28-35

This paper presents an analysis of data obtained by the Federal Aviation Administration related to the characteristics of trailing vortex systems generated by large jet aircraft. Difficulty was experienced in analyzing the data because of the comparatively large spacing of sensors, but some significant information and conclusions can be derived from the analysis. It was found that the velocity field around a vortex produced by a large jet aircraft is defined by a logarithmic variation of circulation with radius. For a lift coefficient of unity, the core diameter was found to be approximately 5% of the mid-span chord while the maximum tangential velocity at the edge of the core was about 70% of the aircraft velocity. Both the diameter and core appear to change in proportion to the lift coefficient. Expressions are developed for predicting the velocity field produced by the trailing vortices from large aircraft. These should be used with caution, however, until additional and more precise data are obtained.

El Hassan, M., Assoum, H. H., Sobolik, V., Vetel, J., Abed-Meraim, K., Garon, A. and Sakout, A.

"EXPERIMENTAL INVESTIGATION OF THE WALL SHEAR STRESS AND THE VORTEX DYNAMICS IN A CIRCULAR IMPINGING JET"

Experimental Fluids, Vol. 52, 2012, pp. 1475-1489.

The wall shear stress and the vortex dynamics in a circular impinging jet are investigated experimentally for $Re = 1,260$ and $2,450$. The wall shear stress is obtained at different radial locations from the stagnation point using the polarographic method. The velocity field is given from the time resolved particle image velocimetry (TR-PIV) technique in both the free jet region and near the wall in the impinging region. The distribution of the momentum thickness is also inspected from the jet exit toward the impinged wall. It is found that the wall shear stress is correlated with the large-scale vortex passing. Both the primary vortices and the secondary structures strongly affect the variation of the wall shear stress. The maximum mean wall shear stress is obtained just upstream from the secondary vortex generation where the primary structures impinge the wall. Spectral analysis and cross-correlations between the wall shear stress fluctuations show that the vortex passing influences the wall shear stress at different locations simultaneously. Analysis of cross-correlations between temporal fluctuations of the wall shear stress and the transverse vorticity brings out the role of different vortical structures on the wall shear distribution for the two Reynolds numbers..

Eldredge, J. D., Colonius, T. and Leonard A.

"A VORTEX PARTICLE METHOD FOR TWO-DIMENSIONAL COMPRESSIBLE FLOW"

Journal of Computational Physics, Vol. 179, 2002, pp. 371-399

A vortex particle method is developed for simulating two-dimensional, unsteady compressible flow. The method uses the Helmholtz decomposition of the velocity field to separately treat the irrotational and solenoidal portions of the flow, and the particles are allowed to change volume to conserve mass. In addition to having vorticity and dilatation properties, the particles also carry density, enthalpy, and entropy. The resulting evolution equations contain terms that are computed with techniques used in some incompressible methods. Truncation of unbounded domains via a nonreflecting boundary condition is also considered. The fast multipole method is adapted to compressible particles in order to make the method computationally efficient. The new method is applied to several problems, including sound generation by corotating vortices and generation of vorticity by baroclinic torque.

Eldredge, J. D., Colonius, T. and Leonard, A.

"A DILATING VORTEX PARTICLE METHOD FOR COMPRESSIBLE FLOW"

Journal of Turbulence, Vol. 3, Paper 036, October 2002, pp. 1-10

Vortex methods have become useful tools for the computation of incompressible fluid flow. In this work, a vortex particle method for the simulation of unsteady two-dimensional compressible flow is developed. By decomposing the velocity into irrotational and solenoidal parts, and using particles that can change volume and that carry vorticity, dilatation, enthalpy, entropy and density, the equations of motion are satisfied. Spatial derivatives are treated using the method of particle strength exchange with high-order-accurate, non-dissipative kernels. The new vortex method is applied to co-rotating and leapfrogging vortices in compressible flow, with the far acoustic field computed using a two-dimensional Kirchhoff surface.

Eldredge, J., Colonius, T. and Leonard, A.

"A VORTEX PARTICLE METHOD FOR COMPRESSIBLE FLOW"

AIAA Paper No. 2001-2641, Anaheim, CA, June 2001

A vortex particle method for the simulation of two-dimensional compressible flows is developed. The computational elements are Lagrangian particles that carry vorticity, dilatation, enthalpy, entropy, and density. The velocity field is decomposed into irrotational and solenoidal parts, which allows its calculation in terms of the particles' vorticity and dilatation. The particle coverage is truncated and incident acoustic waves are absorbed using a suitable boundary treatment. A Kirchhoff surface formulation is developed for computing the far-field sound. The method is applied to a co-rotating vortex pair and the results are discussed.

Eliason, B. G., Gartshore, I. S. and Parkinson, G. V.

"WIND TUNNEL INVESTIGATION OF CROW INSTABILITY"

Journal of Aircraft, Vol. 12, No. 12, December 1975, pp. 985-988

The mutual instability of a trailing vortex pair has been studied in a large wind tunnel. The vortices were visualized using helium-filled soap bubbles and the cores probed with a hot-wire anemometer. Measurements were made to permit calculation of the wing lift, the circulation of the trailing vortices, the diameter of the vortex cores, and the wavelength and plane of oscillation of the unstable vortices. The results show that the linear theories of either Crow or Parks closely predict the characteristics of the instability, the agreement depending on the definition of the vortex core diameter.

Elkhoury, M. and Rockwell, D.

"VISUALIZED VORTICES ON UNMANNED COMBAT AIR VEHICLE PLANFORM: EFFECT OF REYNOLDS NUMBER"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1244-1247.

This Reynolds number dependence of the vortex patterns on a representative UCAV planform, which is distinguished by small sweep angles, can be defined in terms of the onset of pronounced instability/abrupt breakdown of the vortices from the apex of the main body, the effective sweep angle of the vortices from the wing root, and the degree of interaction of the vortices from the apex and the wing root. At relatively low angle of attack, the onset of pronounced instability/breakdown is highly sensitive to Reynolds number, whereas at relatively high angle of attack, it is much less sensitive. The effective sweep angle of the wing root vortex is only a mild function of angle of attack; it is predominantly a function of Reynolds number and tends toward an asymptotic value at high Reynolds number. The Reynolds number at which the vortices from the apex and the wing root cease to interact decreases substantially with a decrease in angle of attack.

Elkinton, C. N., Rogers, A. L. and Ellis, A. F.

"LONG-TERM SITE WIND DATA REPORT, BISHOP AND CLERKS"

Report, March 2006, Renewable Energy Research Laboratory, University of Massachusetts, Amherst, MA.

All the work presented in this Wind Data Report including installation and decommissioning of the meteorological tower and instrumentation, and the data analysis and reporting was performed by the Renewable Energy Research Laboratory (RERL) at the University of Massachusetts, Amherst. This wind measurement station is installed on the Bishop & Clerks US Coast Guard (USCG) automated lighthouse, almost 3 miles south-southeast of Pt. Gammon on Cape Cod, MA. Installed in November of 2000, the wind monitoring station has been in continuous operation to this day. The two anemometers and wind vanes are mounted 15 m (49 ft) above the Mean Low Water Level. This annual report covers the period January 1, 2005 - December 21, 2005. However, the data and graphs presented here only show data from January 1 -- June 23. On June 23, the system at Bishops and Clerks lost the ability to transmit data due to lack of battery charge. This problem was compounded by the inaccessibility of the site, so the problem persisted through the end of 2005. Between January 1 and June 23, the mean recorded wind speed at 15 m was 7.38 m/s (16.5 mph) and the prevailing wind direction was from the north-northeast. The average turbulence intensity at 15 m was 0.11, which is typical for this site. Over the entire year of 2005, the gross data recovery percentage (the actual percentage of expected data received) was 47.6% and the net data recovery percentage (the percentage of expected data which passed all of the quality assurance tests) was 46.9%. For the period when the system was reporting (January 1 - June 23), the gross data recovery percentage was 100.0% and the net data recovery percentage was 98.7%. These indicate that, before the battery failed, the system was working well.

Ellejmi, M., Graham, R., Treve, V., Toussaint, J. and De Visscher, I.

"TECHNICAL FEASIBILITY AND IMPACTS OF REDUCING STANDARD SEPARATION MINIMA IN FINAL APPROACH"

18th Integrated Communications Navigation and Surveillance (ICNS) Conference, April 2018, Herndon, VA.

The Single European Sky ATM Research program (SESAR2020) project for Enhanced Runway Throughput (EARTH), is focused on developing and validating SESAR solutions to increase Runway Throughput. In particular, the project addresses the reduction of the Minimum Radar Separation (MRS) to 2.0NM. The reduction of MRS minima down to 2.0NM on final approach is subject to Required Surveillance Performance (RSP) and is constrained by factors such as satisfying Runway Occupancy Time (ROT). The project studies different technical and operational options to identify cost benefit technical and performance requirements covering safety, capacity, efficiency, resilience, environment and noise, access and equity as well as human performance to facilitate deployment decisions. In this paper we review the need for reducing separation minima on final approach, we provide technical study results covering technology readiness to cope with the operational requirements and the

required surveillance performance, we propose a set of Required Surveillance Performance and we provide the results of a first validation of the concept using real time simulation, we conclude with some recommendation on future steps to evaluate the concept.

Ellis, C. W.

"RECOMMENDATIONS FOR FUTURE AERODYNAMIC RESEARCH"

Proceedings of Third CAL/AVLABS Symposium, Aerodynamics of Rotor, Wing and V/STOL Aircraft, Vol. III, June 1969

The discussion outlines those areas of rotary wing aerodynamics which currently pose the most perplexing problems to the designer and the operator of such aircraft and those areas where aerodynamic improvements are likely to have the largest payoff in either the development of a new vehicle or in the performance of such a vehicle once it has been developed. Limited data is shown to demonstrate the magnitude and nature of the problem (when that data is available). No attempt has been made to correlate this statement of problems with any list of research currently under way, although it is recognized that in many cases such activities are in fact proceeding. The problems are discussed under six general topics: rotor systems, noise, downwash, rotary wing wake, flying qualities, and wind tunnel test techniques.

Ellzey, J. L., Henneke, M. R., Picone, J. M. and Oran, E. S.

"THE INTERACTION OF A SHOCK WITH A VORTEX: SHOCK DISTORTION AND THE PRODUCTION OF ACOUSTIC WAVES"

Physics of Fluids, Vol. 7, No. 1, January 1995, pp. 172-184.

Numerical simulations of a shock interacting with a compressible vortex are presented for shocks and vortices of various relative strengths. The simulations show the effects of the vortex on the shock structure and the structure of the acoustic field generated by the shock-vortex interaction. A relatively weak vortex perturbs the transmitted shock only slightly, whereas a strong vortex leaves the transmitted shock with a structure corresponding to either a regular or Mach reflection. The acoustic wave generated by the interaction consists of two components: a 'quadrupolar' component produced by the initial shock-vortex interaction and the complex reflected shock system. When these waves merge, they form the asymmetric structure seen in experiments.

Ellzey, J. L., Oran, E. S. and Picone, J. M.

"INTERACTION OF A SHOCK WITH A COMPRESSIBLE VORTEX"

Proceedings of the International Symposium on Shock Waves and Shock Tubes, July 1989, Bethlehem, PA, pp. 928-933.

This paper presents a time-dependent two-dimensional numerical simulation of a shock propagating through a compressible vortex. A weak shock, with the fluid velocity behind the shock front very much less than the maximum velocity in the vortex, passes over a shock. The vortex breaks the initial planar shock into four curved shocks that eventually merge.

Elnitsky II, J.

"INTERACTION OF A VORTEX PAIR WITH A FREE SURFACE"

MS Thesis, September 1987, Naval Postgraduate School, Monterey, CA.

The trailing vortices generated by the control planes of submarines give rise to surface signatures in the form of scars and striations. Two counter-rotating vortices were generated in a novel experimental system and their interaction with the free surface was investigated. In addition, the governing equations have been solved using the boundary-element method for a representative Froude number. The results have been expressed in terms of the depth of submergence of the vortices, their mutual induction velocity, and the initial vortex separation. It has been shown that the free surface begins to deform when the vortices are at a distance of about one initial vortex separation from the free surface. The height of the maximum deformation is attained at a normalized time of about 0.1, when the vortices are at a distance of about 0.5 b -zero from the free surface. The elevated part of the surface is bounded by two scars, whose motion is connected to that of the vortices.

El-Ramly, Z.

"INVESTIGATION OF THE DEVELOPMENT OF THE TRAILING VORTEX SYSTEM BEHIND A SWEEPED-BACK WING"

ME/A 75-3, Carleton University, Ottawa, Canada, October 1975

Measurements of the trailing vortex system behind a 35-degree sweptback wing have been made in a low-speed wind tunnel at a mean chord Reynolds number R , of about 500,000 with vortex Reynolds numbers, r/v , up to about 250,000. Spanwise and chordwise loading on the main wing as obtained from pressure distributions, and the character of the boundary layer flow was explored using oil-dot flow visualization and limited hot wire measurements. Mean flow properties of the vortex field have been measured, using a non-nulling 5-hole probe, at two stations 2-1/2 and 5 main wing spans downstream (17.5 and 35 chords respectively). Using a simple strain-gauged balance, the induced rolling moment on two trailing wings (of representative relative scale and aircraft geometry), which intercepted the main wing vortex system, was also measured. Maximum induced rolling moments as well as variation with lateral and vertical position was found.

El-Ramly, Z.

"INDUCED ROLLING MOMENT ON TRAILING WINGS"

AIAA Paper No. 1977-0663, Albuquerque, NM, June 1977

An experimental wind tunnel test program has been conducted to investigate possible scaling parameters for the prediction of the maximum induced rolling moment on a trailing wing. Detailed variation of the induced rolling moment on a following wing in the wake of a generating wing is measured for several lead/trailing combinations. With five wings used ten different combinations were possible covering the trailing/generating span ratio of 0.24 to 1.22. The wings include both straight and swept configurations and the aspect ratio varies between 4 and 8.5. The results show that the maximum induced rolling coefficient depends on the trailing wing aspect ratio and is proportional to both the lift coefficient of the generating aircraft divided by its aspect ratio and to the square root of generating/trailing span ratio. The effect of trailing wing incidence is also examined.

El-Ramly, Z.

"AIRCRAFT TRAILING VORTICES - A SURVEY OF THE PROBLEM"

ME/A 72-1, November 1972, Carleton University, Ottawa, Canada

A survey of the trailing vortices problem is presented. In this report only the work related to vortices shed from high aspect ratio straight or sweptback wings is considered. The survey covers the initial formation and roll-up of trailing vortices, their steady motion and decay, the stability of a trailing vortex pair, atmospheric and ground effects, and vortex breakdown. Experimental results, both full scale and subscale are also reviewed and a survey of the work describing the hazards to aircraft encountering a trailing vortex system is included.

El-Ramly, Z. and Rainbird, W. J.

"WIND TUNNEL MEASUREMENTS OF THE TRAILING VORTEX DEVELOPMENT BEHIND A SWEEPED BACK WING: EFFECT OF SIMULATED JET ENGINES ON THE FLOW FIELD"

AIAA Paper No. 1976-0063, January 1976, Washington, DC.

Measurements of the trailing vortex system behind a semi-span model of a 35-degree sweptback wing of aspect ratio 7 and taper ratio 1/3 have been made in a low-speed wind tunnel at a mean chord Reynolds number of about 500000. Measurements were made for the clean wing configuration (no engines mounted), with two simulated engines mounted but no air injection, and with cold high pressure air injection simulating the jet exhausts. Wing chordwise and spanwise loadings were obtained from pressure distributions. Some mean flow properties of the vortex field have been measured at two stations 2.5 and 5 wing spans downstream using a non-nulling 5-hole probe and a single pitot pressure tube. An overall measure of the vortex field was also obtained by measuring the induced rolling moment on a trailing wing that intercepted the main wing vortex system. Mounting of the two engines on the wing lower surface at representative spanwise locations, but with no exhaust jet simulation, did not greatly affect the rolled-up part of the flow field. However, the still unrolled connecting shear layer was considerably distorted and seemed to be spiraling around the vortex core at a slower rate when compared to the clean wing case. The measured maximum induced rolling moment

on the trailing wing is not significantly changed and is consistent with the observed changes in main wing loading and in the vortex core. With the addition of air injection through the simulated engines no appreciable change in induced rolling moment was measured. The injection has however resulted in small changes in the vortex core position and in the position of the spiraling shear layer relative to it.

El-Ramly, Z. and Rainbird, W. J.

"EFFECT OF WING-MOUNTED DEVICES ON THE TRAILING VORTEX SYSTEM IN THE NEAR FIELD"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 194-206

The paper examines the results of an extensive wind tunnel test program aimed at evaluating the effect of several different devices mounted on a wing on the near field trailing vortex system. The devices used include different wing tip modifications, several spoilers, simulated flap-track fairings, as well as two simulated engines with and without air injection. Only practical tip modifications and spoilers have been incorporated, i.e., only those that appear to be structurally possible with reasonable drag penalties. The devices have been tried first individually and then in combination to see if the reduction in rolling moment is cumulative. Assessment of the effectiveness of the devices, in reducing vortex hazard, is measured as a reduction in the maximum induced rolling-moment coefficient on a following wing of fixed span ratio of 0.24, representative of a light aircraft. All devices tested have resulted in decreases of the vortex hazard. However, no single device by itself produced a substantial decrease in maximum induced rolling moment.

El-Ramly, Z. and Rainbird, W. J.

"FLOW SURVEY OF THE VORTEX WAKE BEHIND WINGS"

Journal of Aircraft, Vol. 14, No. 11, November 1977, pp. 1102-1108

Flow-field surveys of the wake behind three different wings have been carried out in a low-speed wind tunnel. The mean flow properties have been measured using a small non-nulling five-hole probe. The results include the three mean velocity components, complete definition of the viscous wake, and detailed loading on one of the wings. The three components of vorticity were calculated and the vortical wake completely defined. It was found that the vortical wake always is contained within the viscous wake (region of total pressure loss). The vortex system is never fully rolled up, in the traditional sense, within the reasonably large downstream distance tested of 13 wing spans. The overall lift coefficient calculated from the distribution of streamwise component of vorticity is found to be smaller (87-100%) than that measured directly on the wing. The total circulation accounted for, at any streamwise station, decreases slightly with downstream distance. Comparison was made between the measured tangential velocity profiles and circulation distribution and those calculated using Betz theory, based on measured spanwise loading. Agreement is reasonable over a radius more or less equal to that of the vortex viscous core ($<0.25 b/2$). Outside of this region, the Betz model assumes

that roll-up is complete when, in fact, it is not. Agreement is also poor very near the vortex center because of the strong viscous effects there.

El-Ramly, Z. and Rainbird, W. J.

"COMPUTER-CONTROLLED SYSTEM FOR THE INVESTIGATION OF THE FLOW BEHIND WINGS"

Journal of Aircraft, Vol. 14, No. 7, July 1977, pp. 668-674

A completely computer-controlled wind-tunnel test facility for measurements of the vortical flow field behind a lifting swept-back wing is described. The vortex generator model is a pressure-plotted root-mounted half-wing. Flow field measurements were made using a pre-calibrated non-nulling blunted conical five-hole probe. The program developed can calculate and plot, on-line, the three components of velocity and vorticity, the total pressure loss coefficient, and the circulation distribution. As a result of these automated flow field measurements, it was possible to account for almost all the vorticity shed from the wing.

El-Ramly, Z. and Rainbird, W. J.

"EFFECT OF SIMULATED JET ENGINES ON THE FLOWFIELD BEHIND A SWEPT-BACK WING"

Journal of Aircraft, Vol. 14, No. 4, April 1977, pp. 343-349

Measurements of the vortex behind a swept-back wing have been made in a low-speed wing tunnel. Results have been taken with a clean wing, with engines mounted in representative positions, and with and without jet exhaust simulation. Only cruising flight conditions are simulated. Loading on the wing has been obtained from pressure distribution measurements. Flow field properties and the rolling moment on a trailing wing have been measured at 2-1/2 and 5 wing spans downstream. The concentrated tip vortex structure is essentially unaffected by the engines but the remaining shear layers are considerably distorted by the pylon-nacelles. The maximum induced rolling moment on the trailing wing is only slightly reduced by the present engine installation or the simulated jet exhaust.

El-Ramly, Z., Rainbird, W. J. and Earl, D. G.

"WIND TUNNEL MEASUREMENTS OF ROLLING MOMENT IN A SWEPT-WING VORTEX WAKE"

Journal of Aircraft, Vol. 13, No. 12, December 1976, pp. 962-967

Some measurement of the trailing vortex system behind a 350 sweptback, tapered wing have been made in a low-speed tunnel at a chord Reynolds number of 0.5×10^6 . Detailed wing loading was obtained from pressure distributions. Mean flow properties have been measured, using a non-nulling 5-hole probe, at two stations: 2-1/2 and 5 main wing spans downstream. Induced rolling moment on two trailing wings, which intercepted the main wing vortex system was also measured. Judged by the circulation around the core, the shear layers had not fully rolled up at the 2-1/2 station. Also, no

further appreciable roll-up occurred at the 5b station. Furthermore, there was very little difference between the induced rolling moments measured at the two stations.

Elsayed, O. A., Asrar, W., Omar, A. A. and Kwon, K.

"EVOLUTION OF NACA23012 WAKE VORTICES STRUCTURE USING PIV"

Journal of Aerospace Engineering, Vol. 25, Issue 1, January 2012, pp. 10-20.

The formation and development of a wing-tip vortex in a near and extended near field were studied experimentally. A swept-back tapered wing with a NACA230112 cross-section was used as a vortex generator. Particle image velocimetry (PIV) as a whole field velocity measurement technique was used in a low-speed wind tunnel to measure and characterize the wing-tip vortex. Wake structures at successive downstream planes crosswise to the axis of the wake vortices were evaluated in internal and external core radius, maximum tangential velocities, vorticity, and circulation distributions. The effect of angle of attack on vortex parameters was examined at one downstream location. Internal core radius and circulation distributions were nearly constant along the downstream direction. A direct dependence of the circulation and tangential velocity distribution on the angle of attack was evident. The centers of the wing-tip vortices scatter in a circle of radius nearly equal to 1 percent of the mean wing chord. Meandering amplitudes showed no direct dependence on the vortex strength but increase along the downstream direction. Good agreement was obtained between the theoretical exponential vortex model and the measured data. Computed induced rolling moment coefficients generated by the wing are within the full roll control capability of a follower aircraft.

Elsayed, O. A., Asrar, W., Omar, A. A. and Kwon, K.

"INFLUENCE OF DIFFERENTIAL SPOILER SETTINGS ON THE WAKE VORTEX CHARACTERIZATION AND ALLEVIATION"

Journal of Aircraft, Vol. 47, No. 5, Sept.-Oct. 2010, pp. 1728-1738.

Experimental investigations using particle image velocimetry technique have been carried out for the evolution of the differential spoiler setting capabilities in modifying the span-wise wing load and further reduce the wake vortex hazard. The aircraft half model (at high lift configuration) was investigated for two differential spoiler settings. Results reveal a noticeable inboard shift of spanwise wing loading. Implementation of a differential spoiler setting results in a substantial redistribution of the flap tip vortex circulation with an increase in the diameter of the merged vortex by a factor of up to 2.72 relative to the undisturbed flap tip vortex. Inspection of the cross-stream distribution of axial vorticity shows a reduction by a factor of up to 2.33 in the peak vorticity value. A 44 percent decrease of the maximum crossflow velocity relative to the undisturbed flap tip vortex crossflow velocity was recorded for the case of deployed spoilers. Finally, assessment of the differential spoiler capabilities as a wake vortex attenuation device reveals that, while position of the maximum induced rolling moments in the flap tip area is little influenced by the differential spoiler setting, the maximum induced rolling

moments in the flap tip area is little influenced by the differential spoiler setting, the maximum induced rolling moment coefficient was reduced to nearly one third of the undisturbed flap tip vortex value.

Elsayed, O. A., Asrar, W., Omar, A. A., Kwon, K. and Jung, H.

"EXPERIMENTAL INVESTIGATION OF PLAIN- AND FLAPPED-WING TIP VORTICES"

J. Aircraft, Vol. 46, No. 1, Jan.-Feb. 2009, pp. 254-262

Particle image velocimetry was used in a low-speed wind tunnel to investigate and characterize wing tip vortex structure. A rectangular wing of a subsonic wall interference model was used as a vortex generator in two different configurations: (1) plain wing and (2) flapped wing with the trailing-edge flap extended at 20 degrees. Vortex flow quantities and their dependence on angle of attack at Reynolds numbers of 32800 and 43800 were evaluated. Assessment of measured data reveals that the peak values of tangential velocities, vortex strength, and vorticities are directly proportional to the angle of attack. The vortex core radius grows slowly as the angle of attack is increased. Both plain and flapped configurations showed similar trends. The peak tangential velocities and circulation almost doubled when the flapped configuration was used instead of the plain wing.

Elsayed, O. A., Kwon, K., Asrar, W. and Omar, A. A.

"INDUCED ROLLING MOMENT FOR NACA4412 PLAIN AND FLAPPED WING"

Aircraft Engineering and Aerospace Technology: An International Journal, Vol. 82, No. 1, 2010, pp. 23-31.

This paper describes the detailed variation of the induced rolling moment generated by a plain and flapped NACA4412 wing on a follower aircraft wing derived from a particle image velocimetry velocity field measurement. A rectangular wing of a subsonic wall interference model is used as a vortex generator in two different configurations: plane wing of NACA4412 cross-section profile; and flapped wing with trailing edge flap of NACA0012 cross-section profile extended at 20 degrees. Results obtained showed that the maximum induced rolling moment coefficient depends on the strength of the vortex produced by the generating aircraft wing and increases linearly with the increment of the angle of attack. The paper provides an insight on the effects of different angles of attack for plain and flapped wings on the induced rolling moment coefficient and therefore, the hazard imposed on the following aircraft can be estimated.

Elsayed, O. A., Omar, A. A., Asrar, W. and Kwon, K.

"EFFECT OF DIFFERENTIAL SPOILER SETTINGS ON THE WAKE VORTICES OF A WING AT HIGH-LIFT CONFIGURATION"

Aerospace Science and Technology, Vol. 15, 2011, pp. 555-566.

An experimental investigation has been carried out to evaluate the capabilities of differential spoiler setting (DSS) in modifying the wingspan loading. The particle image velocimetry (PIV) technique was used in a low-speed wind tunnel facility to measure wake velocities at four locations downstream of the half model in the near wake field. The model was investigated at a high lift configuration (called base-line configuration) and at two different DDSs believed to modify the baseline wingspan loading. Those settings were obtained by deflecting spoiler number 1 at 10 degrees (outboard loading case 1) and spoiler numbers 2, 3, 4, 5 and 6 at 5 degrees (outboard loading case 2). Results reveal that, introducing a highly turbulent oscillatory wake due to a spoiler in the flow field increases the flap tip vortex meandering amplitude by up to 2.17 times the flap tip vortex core radius value. This result emphasizes the importance of using spatially corrected data in extracting mean vortex parameters values. Moreover, meandering can lead to accelerated vortex breakdown especially when the vortex motion intensifies further downstream contributing favorably to wake vortex alleviation. Integration of the streamwise vorticity shows a mild outboard wing loading shift for outboard loading case 1, while the outboard loading case 2 leads to a reduction in the span-wise circulation with no change in the spanwise load distribution.

Elsenaar, A.

"VORTEX FORMATION AND FLOW SEPARATION: THE BEAUTY AND THE BEAST IN AERODYNAMICS"

NLR-TP-2000-421, August 2000, National Aerospace Laboratory, Amsterdam, The Netherlands.

Flow separation and vorticity generation are closely connected. When the flow leaves the trailing edge of a wing, a vorticity layer is formed, directly related to the lift of the wing and carrying streamwise vorticity. Boundary layers, in which the viscous flow very close to the wing surface is confined, carry vorticity in crosswise direction, perpendicular to the local flow direction at the boundary layer edge. Streamwise and crosswise vorticity are carried downstream in the wake. When boundary layers separate from the surface ahead of the trailing edge, the flow characteristics are essentially similar though more complex. Vortex sheet separations of a more conical nature can be found on the upper surface of delta wing configurations or slender bodies of revolution. They can be regarded as a skeleton of vortex lines again with a strength related to lift and induced drag. These separations might be induced by sharp edges, as is the case for the sharp-edged delta wing, or on smooth bodies, by boundary layer separation. Vortex sheet separations are not confined to conical geometries but can be found in all kinds of flow. Other separations on the wing will have a more bubble-like nature, confined to a region close to the surface, and contributing to the viscous drag. The distinction between streamwise and crosswise vorticity is preserved in the development of the wake downstream resulting finally, most often, in a pair of counter-rotating vortices that are of great concern from a safety point of view for landing aircraft. A simplified relation based on lift and induced drag can be used to estimate the strength of the vortices. They persist very long until the vortex pair breaks up through a basic instability very far downstream. A review is presented of these various types of separations and related vortex development, partly based on concepts as can be found in the literature. This is illustrated with practical examples of separations both from experiments and from CFD calculations.

Elsenaar, A.

"OPTIMIZATION OF THE (INVISCID) UPPER LIMIT OF THE ROLLING MOMENT INDUCED BY A VORTEX PAIR"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

The vortex center is assumed to be surrounded by a viscous and a vorticity core. Outside the vorticity core the flow is irrotational. All vorticity (for a fully rolled-up vortex) is thought to be concentrated within the vorticity core. For the high Reynolds numbers of actual aircraft, the viscosity core is so small that it can be neglected: the vortex flow field is basically inviscid. The (vorticity) core radius follows then directly from the induced drag relation when a family of velocity distributions is assumed to apply inside the vorticity core. The velocity distributions that can be calculated from these assumptions can be regarded as a high Reynolds number upper limit for the vortex flow field. There is some experimental evidence that this upper limit is approached when roll-up is complete and in the absence of vortex decay (no external turbulence). This velocity distribution can subsequently be used to calculate the induced rolling moment for a follower A/C that flies right into the vortex center. The two parameters, vortex distance s and induced drag factor e can (within limits) be selected such that an optimum induced rolling moment results. Some examples will be given. The analysis suggests that the best compromise from the point of view of separation distances is obtained for an inboard loaded wing with a low induced drag. In practice decay due to external turbulence cannot be neglected. Other limitations, also from the point of view of vortex development (like multiple vortices) restrict the load distributions that can actually be achieved. But the present model might give some feeling for the possibilities to reduce wake vortex strength by design.

Elsenaar, A.

"VORTEX FORMATION AND FLOW SEPARATION: THE BEAUTY AND THE BEAST IN AERODYNAMICS"

Aeronautical Journal, December 2000, pp. 615-633

I have tried in this lecture to present a phenomenological view of separation and vortex formation. I have shown some examples of the complicated flow field on wings and slender bodies, a flow field that can be split into a field with streamwise and cross wise vorticity as clearly noticeable behind the wing. From there on this complex flow field simplifies, resulting in one or sometimes two vortex pairs. And this simplified flow field finally breaks up through vortex decay or instabilities into chaotic motion at smaller scales.

Elsenaar, B.

"COMPUTER SIMULATIONS OF AIRCRAFT WAKE VORTICES: GOOD ENOUGH TO QUANTIFY SAFETY?"

Proceedings ECCOMAS Computational Fluid Dynamics Conference, September 2006, Egmond aan Zee, The Netherlands.

To see if capacity can be increased without loss of safety, computer simulations are made of the air traffic situation, the generation and the decay of wake vortices and the flight mechanical effects on the follower aircraft when a vortex is encountered. The aim is to quantify both the capacity change (e.g. expressed as the number of landings per hour) and the safety (e.g. expressed as a target level of safety). The prediction of the weather dependent decay of wake vortices is a critical issue here. Large eddy simulations that include the specific features of the weather can describe the decay of vortices in a physically correct way. These calculations can be imbedded in a probabilistic safety assessment to calculate with Monte Carlo simulations the level of safety.

Elsenaar, B., Sulejmanovic, B. and Lentjes, V.

"THE VORTEX LIFE TIME FROM THE MEMPHIS DATA AND SOME IMPLICATIONS"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

The ability to predict the wake vortex position and strength as a function of the weather conditions is of paramount importance for any (probabilistic) safety analysis or wake vortex advisory system. Advection by wind and the decay of the vortex strength up till its final stage as a broken-up vortex, are the critical processes here. The talk will focus on the question how the time that the vortex breaks-up (the vortex demise time, VDT) can be correlated with weather conditions. The analysis is restricted to the 'out of ground effect' data collected at Memphis. It is widely accepted that the VDT, when made dimensionless with the corresponding length (distance between the two vortices) and velocity (descent speed of the vortex pair), can be expressed as a function of the atmospheric turbulence, preferably the eddy dissipation rate (EDR). Moreover, theoretical work has indicated strong effects of stratification. The available experimental evidence shows considerable scatter that makes it difficult to validate these relations for realistic weather conditions. EDR is usually measured near the ground (typically at 40 m) and the available measurements indicate very large fluctuations with time. One can argue if these values are sufficiently representative for an indication of the VDT at greater heights. To clarify this, the group of Thomas Gerz (DLR) has defined specific weather classes (so called Wake Vortex Behavior Classes) to correlate the weather conditions with the more readily available measurements of wind shear S and stratification N (expressed as the Brunt Vaisala frequency). It is only a small step further to treat S and N as truly independent variables, what makes sense from a physical point of view: the effect of external turbulence and of stratification are distinct physical mechanisms. It will be shown that the correlation can be improved in this way. The question will finally be raised how relevant these findings are if one wants to increase capacity without affecting safety e.g. by using a Wake Vortex Advisory System. This will of course depend on the local weather conditions (in a statistical sense) but an order of magnitude analysis can be made both for arriving and departing aircraft for weather statistics as follows from the Memphis recordings. The study is limited in the sense that only wakes out of ground effects are considered, whereas for landing situation the behavior near the ground is the most critical phase. However, for departing aircraft, where the departing tracks are distributed over a much wider area, the VDT is expected to be an important parameter. In future work ground effects are to be included as well as an application to other data sets, notably with a larger variety in wingspan to better assess the usual assumptions to non-dimensionalize the data.

Emanuel, M., Catapano, S., Sherry, J., Berger, J., Robinson, P., Prince, J., Cornman, L., Meymaris, G., Goodrich, K., Mulally, D., Dana, R., Stone, R. and Taylor, M.

"PRELIMINARY FINDINGS OF IN SITU EDR RESEARCH"

AMS Fourth Aviation, Range, and Aerospace Meteorology Special Symposium, February 2014, Atlanta, GA.

The preliminary findings of the project found that all existing in situ EDR implementations calculate mean EDR accurately and consistently for homogeneous turbulence. However, all existing in situ EDR implementations employ different data sampling window lengths, parameter settings, and methodologies, yielding inconsistent peak EDR values in very sudden intense turbulence. To reduce these inconsistencies between implementations, the project is performing a sensitivity analysis as continuing research with the goal of reducing inconsistencies across algorithms. The findings of the sensitivity analysis, along with a more in-depth narrative of the project's discovery, process, findings, and performance recommendations can be found in the project's FAA EDR Standards Report, scheduled for delivery to the FAA in July, 2014.

Emanuel, M., Sherry, J., Catapano, S., Cornman, L. and Robinson, P.

"IN SITU PERFORMANCE STANDARD FOR EDDY DISSIPATION RATE"

AMS 16th Conf. of Aviation, Range, and Aerospace Meteorology, 2013, Austin, TX.

The EDR Standards Project has been initiated by the FAA to perform the research required to develop performance standard recommendations for in situ EDR. Equally essential will be the project's recommendations for in situ EDR data encoding and label definitions. The project is leveraging information learned through the EDR literature search and collaboration outreach with key stakeholders. The knowledge gained will assist the team in development of a standardization process, which provides the artifacts required to support recommendations for in situ EDR performance standards. The standardization of in situ EDR will support the greater aviation community through the increase in fidelity and accuracy of in situ turbulence information. EDR performance standards will facilitate greater real time turbulence situational awareness and drive enhancements in safety, capacity, and operational efficiencies.

Emeis, S., Munkel, C., Vogt, S., Muller, W. J. and Schafer, K.

"ATMOSPHERIC BOUNDARY-LAYER STRUCTURE FROM SIMULTANEOUS SODAR, RASS, AND CEILOMETER MEASUREMENTS"

Atmospheric Environment, Vol. 38, 2004, pp. 273-286.

A comparison of the determination of boundary-layer structures by a SODAR, by a RASS, and by a ceilometer is presented. One important structure is the mixing-layer height (MLH). The comparison is

focused on 3 days with an evolution of a convective boundary layer over a larger city in Germany. The three instruments give information that partly agree and partly complement each other. By this, a picture of the diurnal evolution of the vertical structure of this urban boundary layer is presented. The ceilometer gives information on the aerosol content of the air and the RASS provides a direct measurement of the vertical temperature distribution in the boundary layer. The RASS and the ceilometer add information on the moisture structure of the boundary layer that is not detected by the SODAR. On the other hand, this comparison validates known techniques by which the MLH is derived from SODAR data. Especially the temperature information from the RASS agrees well with lifted inversions derived from the analysis of the SODAR data. The ceilometer, being the smallest instrument, has a potential to be used in future MLH studies.

Emeis, S., Siedersleben, S., Lampert, A., Platis, A., Bange, J., Djath, B., Schulz-Stellenfleth, J. and Neumann, T.

"EXPLORING THE WAKES OF LARGE OFFSHORE WIND FARMS"

The Science of Making Torque from Wind (TORQUE 2016), published in IOP Journal of Physics: Conference Series, Vol. 753, 2016, pp. 092014-1 to 092014-11.

Offshore meteorological characteristics set specific conditions for the operation of offshore wind farms. One specific feature is low turbulence intensity which on the one hand reduces loads on turbines but on the other hand is the reason for much longer turbine and farm wakes than over land. The German Government is presently funding a research project called WIPAFF (WInd PARK Far Field) which heads for the analysis of properties and impacts of offshore wind park far fields. The focus is on the analysis of wind farm wakes, their interaction among each other and their regional climate impact. This is done by in-situ, extensive aircraft and satellite measurements and by operating meso-scale wind field models and an analytical wind farm model.

Emmer, D. S.

"EXPERIMENTAL STUDIES OF TRANSONIC AIRFOIL TRAILING EDGE AND WAKE FLOWFIELD PROPERTIES"

Ph.D. Thesis, 1984, Ohio State University, Columbus, OH

An experimental investigation of several of the trailing edge and wake turbulence properties for a NACA 84A010 airfoil section was completed. The experiment was conducted at The Ohio State University Aeronautical and Astronautical Research Laboratory in the 6-inch x 22 inch transonic flow facility. For both angles of attack, the turbulence intensities and turbulence kinetic energy were observed to decay in the streamwise direction. In the fair wake, the turbulence intensities were nearly isotropic for the non-lifting case. For the two-degree case, the horizontal component of the turbulence intensity was observed to be substantially higher than the vertical component. For each survey, the data demonstrated excellent repeatability with a high degree of spatial resolution. The results of this research should provide guidance for the development, verification, and improvement of turbulence modeling.

Engel, M. A. and Devenport, W. J.

"A WIND TUNNEL INVESTIGATION OF A WING-TIP TRAILING VORTEX"

VPI-AOE-218, May 1995, Virginia Polytechnic Inst. and State Univ., Blacksburg, VA

The 3'x2' Subsonic Wind Tunnel was used to study a wing-tip trailing vortex during its development at the wingtip and at 10 chord lengths downstream. The vortex was found to be well developed by 10 chord lengths. Helium bubble flow-visualization was used to study the development of the vortex in the near-tip regions. Hot wire anemometry was used to study the vortex at 10 chord lengths. Two vortices were found in the tip-flow studies, a primary vortex formed on the suction side surface of the wingtip and a weaker secondary vortex formed on the endcap. The primary vortex lifts from the surface of the wingtip as it proceeds along the chord. The vortex core radius, peak tangential velocity, and core circulation increase with increasing angle of attack. The tangential velocity profiles and axial vorticity profiles indicate the development of inner and outer core regions by 5.0 degrees angle of attack. The regions become increasingly differentiated with increasing angle of attack. The inner and outer regions appear to be associated with the primary and secondary tip vortices, respectively.

Engelbart, D., Steinhagan, H., Gorsdorf, U., Neisser, J., Kirtzel, H. J. and Peters, G.

"FIRST RESULTS OF MEASUREMENTS WITH A NEWLY-DESIGNED PHASED-ARRAY SODAR WITH RASS"

Meteorology and Atmospheric Physics, Vol. 71, 1999, pp. 61-68.

At a special measuring site for boundary-layer studies as well as land-surface processes the Meteorological Observatory Lindenberg of the German Weather Service (DWD) has recently put into operation a newly-designed phased-array SODAR/RASS, which has been developed by METEK on behalf of the DWD. This system provides the vertical profiles of the three-dimensional wind vector in the boundary layer on an operational basis and is furthermore suitable for getting information on the profile of virtual temperature up to about 400 m in height based on the addition of RASS components. The following paper describes both the technique of this SODAR/RASS and the various modes of operation as well as the different options in managing the system. First evaluations on the data availability concerning the maximum height coverage will give an impression on the system's capabilities. Finally, the accuracy of the derived profiles of winds and temperature will be investigated by means of comparisons of the SODAR/RASS data with measurements of a six-sonde tethered-balloon system as well as meteorological data of a 99 m tower in the vicinity of the system.

Engholm, C. D., Robasky, F. M., Banerjee, A. and McPartland, M.

"EXAMINATION OF MODE S EHS WIND OBSERVATIONS FOR USE IN WAKE VORTEX MITIGATION APPLICATIONS"

AIAA Paper 2018-3353, June 2018, Atlanta, GA.

Air transport continues to be an important part of our transportation system. As demand grows, increasing throughput becomes a challenge, driven partly by the need to maintain a safe distance between planes in order to mitigate the effects of wakes generated by leading aircraft. Wake vortex trajectories and strength are impacted by the winds, a fact which can be leveraged to safely decrease spacing between aircraft and thereby increase throughput when wind characteristics reduce the likelihood of wake encounters. Procedures to reduce spacing require reliable forecasts of wind to ensure that winds remain suitable for the entire duration the procedure. The major challenges these forecasts face are a lack of real-time wind information in the region of interest and lack of high fidelity, high-resolution observations to provide a validation source for development. Aircraft systems that report wind conditions are a logical solution to the problem and are routinely available through the Meteorological Data Collection and Reporting System (MDCRS). Unfortunately, in many regions of interest, the low spatial and temporal resolution and high latency of these reports limit their utility for wind forecasts and/or validation sources for wake applications. Aircraft derived Observations (AdOs) of meteorological conditions from Mode S Enhanced Surveillance (EHS) data have the advantages of other aircraft reports but also have much higher spatial and temporal resolution and lower latency compared to MDCRS. Therefore, they are under consideration to address both wind forecast challenges. Toward this end, simultaneous LIDAR and Mode S EHS derived observations were collected over an extended period in the proximity to Boston Logan International Airport (KBOS). Archived MDCRS data were also available for comparison. This paper presents a comparison of these observation sets that will speak to the applicability of the Mode S EHS data as a validation source. Further, an examination will be made of how current wind forecasts for use in wake vortex mitigation systems might be improved by access to these data. While in this paper we leverage the growing equipage of Mode S EHS technologies to gain access to AdOs and begin to understand their potential utility in current and future applications, results are applicable to other AdO sources which may be available in the future.

Ennis, R. L. and Zhao, Y. J.

"DEFINING APPROPRIATE INTER-AIRCRAFT SEPARATION REQUIREMENTS"

AIAA Paper No. 2004-6203, Chicago, IL, September 2004

To maintain minimum separation standards between two aircraft, proper avoidance maneuvers must be initiated before their relative separation reaches the minimum separation due to aircraft dynamics, controller and pilot response delays, and other delays. This paper presents the concept and a systematic procedure for the calculation of required action thresholds, which is the time or distance when the conflict resolution process must begin to maintain minimum separation requirements. It sets an upper boundary or latest alert time for the conflict detection and resolution process. In this paper, 5 main segments in the process of conflict resolution are identified and modeled: state information acquisition, comprehension and decision, communication, pilot response, and aircraft maneuver. Then, the models of the five segments are brought together in a simulation where a robust aircraft maneuver time can be calculated through extensive simulations. The models and simulation are then used to determine the required action threshold. Three example scenarios are studied to illustrate the determinations of appropriate required action thresholds.

Ennis, R. L. and Zhao, Y. J.

"A FORMAL APPROACH TO THE ANALYSIS OF AIRCRAFT PROTECTED ZONE"

Air Traffic Control Quarterly, Vol. 12, No. 1, 2004, pp. 75-102

The protected zone represents a region around a given aircraft that no other aircraft should penetrate for the safety of both aircraft, and defines the minimum separation requirements. In this paper, three major components of the protected zone and their interplays are identified: a vortex region, a safety buffer region, and a state-uncertainty region. A systematic procedure is devised for the analysis of the state-uncertainty region. In particular, models of trajectory controls are developed that can be used to represent different modes of pilot and/or autopilot controls, such as path feedback and non-path feedback. Composite protected zones under various conditions are estimated, and effective ways to reduce sizes of protected zones for advanced air traffic management are examined.

Eppler, R.

"INDUCED DRAG AND WINGLETS"

Technical Soaring, Vol. XX, No. 2, 1996, pp. 89-96.

A simple method has been presented which allows consideration of an important second order term in the theory of induced drag. This term is the induced lift, which probably is the most important effect of the wake rollup. The new theory explains the difference between positive and negative dihedral which has been demonstrated by model experiments. Many more results can be expected from this theory.

Epps, B. P.

"REVIEW OF VORTEX IDENTIFICATION METHODS"

AIAA Paper 2017-0989, January 2017, Grapevine, TX.

While vortex identification is a problem of broad interest in fluid mechanics, the fluid mechanics community has not yet converged on a universally-accepted definition of a vortex. The goal of this paper is to provide a comprehensive review of the state of the art, to bring the community one step closer to answering the deceptively complicated question: What is a vortex.

Epstein, R. J. and Bliss, D. B.

"FREE VORTEX CALCULATIONS USING ANALYTIC/NUMERICAL MATCHING WITH SOLUTION PYRAMIDING"

AIAA Journal, Vol. 33, No. 5, May 1995, pp. 894-903

The motion of a free vortex system is predicted using a novel method called analytical/numerical matching (ANM). Analytical/numerical matching is a hybrid mathematical and numerical technique that results in a new problem formulation with high accuracy and increased computational efficiency. The approach capitalizes on the disparity of characteristic length scales that occur in many fluid dynamics problems. Accordingly, many problems can be decomposed into two distinct problems involving a local high-resolution near field, often solvable analytically, and a global, low-resolution far field, solved numerically. The ANM technique breaks the free vortex problem into these local and global problems, each of which being easier and more efficient to solve than the traditional problem formulation. In addition, the ANM decomposition can be repeated to form a hierarchy of nested problems of increasing resolution using a method called pyramiding. The ANM method with pyramiding, called ANM/P, is studied to assess its accuracy and computational efficiency for two-dimensional and three-dimensional vortex dynamics problems. In calculations of vortex sheet rollup and vortex ring motion and interactions, this method was found to be relatively easy to implement and exhibited reductions in computational time from a factor of three to more than an order of magnitude.

Epstein, R. J. and Bliss, D. B.

"WAKE GENERATION AND COMPRESSIBILITY EFFECTS IN UNSTEADY AERODYNAMICS"

AIAA Journal, Vol. 37, No. 3, March 1999, pp. 393-396

The necessity for modeling unsteady compressible wake effects in compressible unsteady aerodynamics is addressed. The role of compressibility during the initial stages of wake formation is determined. It is shown that a compact portion of the wake, that which is closest to the trailing edge, is most important regarding wake compressibility for many subsonic flows. A simple approximation is derived that determines the relative magnitude of the compressible wake length that must be used in a calculation.

Epstein, R. J., Carbonaro, M. C. and Caudron, F.

"EXPERIMENTAL INVESTIGATION OF THE FLOWFIELD ABOUT AN UNSWEPT AFTERBODY"

Journal of Aircraft, Vol. 31, No. 6, November-December 1994, pp. 1281-1290.

In general, the flow field about the aft portion of an aircraft fuselage employing an un-swept afterbody is complex, and can have a detailed vortex structure. Directional pressure probe measurements show that the afterbody wake evolution is weakly dependent on the Reynolds number. Pressure taps are used to investigate the effect of base slant on the base pressure distribution. The base pressure distribution is found to increase along the upswept ramp in the freestream direction. Using oil flow visualizations general conclusions are drawn about the surface flow topology. Two distinct regions of flow separation are identified. An analytical model of the crossflow wake structure is developed from the experimental data. This model allows for conclusions to be drawn about the crossflow vortex structure and provides simple analytical expressions for the vorticity and swirl velocity distributions in the crossflow plane.

Erickson, G. E., Peake, D. J., Del Frate, J., Skow, A. M. and Malcolm, G. N.

"WATER FACILITIES IN RETROSPECT AND PROSPECT -- AN ILLUMINATING TOOL FOR VEHICLE DESIGN"

Aerodynamic and Related Hydrodynamic Studies Using Water Facilities, AGARD-CP-413, Oct. 1986, pp. 1-1 to 1-28.

Water facilities play a fundamental role in the design of air, ground, and marine vehicles by providing a qualitative, and sometimes quantitative, description of complex flow phenomena. Water tunnels, channels, and tow tanks used as flow-diagnostic tools have experienced a renaissance in recent years in response to the increased complexity of designs suitable for advanced technology vehicles. These vehicles are frequently characterized by large regions of steady and unsteady three-dimensional flow separation and ensuing vortical flows. The visualization and interpretation of the complicated fluid motions about isolated vehicle components and complex configurations in a time- and cost-effective manner in hydrodynamic test facilities is a key element in the development of flow control concepts and, hence, improved vehicle designs. This paper presents a historical perspective of the role of water facilities in the vehicle design process. The application of water facilities to specific aerodynamic and hydrodynamic flow problems is discussed, and the strengths and limitations of these important experimental tools are emphasized.

Eriksson, S., Svard, M. and Nordstrom, J.

"SIMULATIONS OF GROUND EFFECTS ON WAKE VORTICES AT RUNWAYS"

Center of Turbulence Research, Annual Research Briefs, 2007, pp. 379-388.

In this paper the interaction between two counter-rotating vortices is examined, and the performance of a newly developed finite difference code is discussed. The Reynolds numbers considered are low to medium, and the flow is compressible. Most of the computations are performed in a two- dimensional domain, with different grid sizes, Reynolds number and order of accuracy of the scheme. Finally, a three-dimensional computation is made to examine the relevance of the two dimensional model.

Eriksson, S., Svard, M. and Nordstrom, J.

"SIMULATIONS OF GROUND EFFECTS ON WAKE VORTICES AT RUNWAYS"

Report 2007-019, June 2007, Uppsala University, Uppsala, Sweden

In this paper the interaction between two counter-rotating vortices is examined, and the performance of a newly developed finite difference code is discussed. The Reynolds numbers considered are low to medium, and the flow is compressible. Most of the computations are performed in a two- dimensional domain, with different grid sizes, Reynolds number and order of accuracy of the scheme. Finally, a three-dimensional computation is made to examine the relevance of the two dimensional model.

Erlebacher, G., Hussaini, M. Y. and Shu, C.-W.

"INTERACTION OF A SHOCK WITH A LONGITUDINAL VORTEX"

ICASE Report No. 96-31 (NASA CR-198332), May 1996, Institute for Computer Applications in Science and Engineering, NASA Langley Research Center, Hampton, VA.

In this paper we study the shock/longitudinal vortex interaction problem in axisymmetric geometry. Linearized analysis for small vortex strength is performed, and compared with results from a high order axisymmetric shock-fitted Euler solution obtained for this purpose. It is confirmed that for weak vortices, predictions from linear theory agree well with results from nonlinear numerical simulations at the shock location. To handle very strong longitudinal vortices, which may ultimately break the shock, we use an axisymmetric high order essentially non-oscillatory shock capturing scheme. Comparison of shock-captured and shock-fitted results are performed in their regions of common validity. We also study the vortex breakdown as a function of Mach number ranging from 1.3 to 10, thus extending the range of existing results. For vortex strengths above a critical value, a triple point forms on the shock, and a secondary shock forms to provide the necessary deceleration so that the fluid velocity can adjust to downstream conditions at the shock.

Esquieu, S., Meheut, M., von Geyr, H. F. and Brodersen, O.

"FAR-FIELD DRAG EXTRACTION FROM NUMERICAL SOLUTIONS AND WAKE SURVEYS"

7th ONERA-DLR Aerospace Symposium, Toulouse, France, October 4-6, 2006

This paper focuses on ONERA drag extraction methods from numerical simulations and flow field wake surveys. A new far-field drag extraction software (FFD72) allows, thanks to its face-based data structure, to extract drag as well from structured (elsA cell-centered) as from unstructured (TAU cell-vertex) RANS solutions. By field analysis, this approach provides a drag breakdown into its physical components i.e. viscous drag, wave drag and lift-induced drag. To carry out such a drag breakdown from wind tunnel tests another method has been developed and allows the evaluation of these physical components from flow field wake measurements.

Estes, M. J.

"DETECTION OF HIGH ALTITUDE AIRCRAFT WAKE VORTICES USING INFRARED DOPPLER LIDAR: AN ASSESSMENT"

AFIT/GEO/ENP/90D-1 [MS Thesis], December 1990, Air Force Inst. of Tech., Wright-Patterson AFB, OH

The feasibility is studied of air-to-air detection of high-altitude aircraft wake vortices at long ranges using infrared Doppler lidar. The purpose of this technique is to detect otherwise stealthy aircraft. Three laser wavelengths were analyzed: 1.064, 2.091, and 9.115 microns. Analysis revealed that the spectral width of the return signal from an aircraft wake presented a good signature for detection. Based on the analysis, a minimum signal-to-noise ratio of 0 dB was established. Detection performance was then analyzed using signal-to-noise ratio calculations for backscatter by ambient atmospheric

aerosols, jet engine exhaust soot particles, and condensation trail ice particles. Results indicated that atmospheric aerosols alone were not sufficient for detection in clean atmospheric regions. Backscatter enhancement by soot particles did appear to be sufficient for detection out to 80 km. Enhancement by condensed ice particles in wake contrails provided detection well beyond 100 km in range. The shorter wavelength lidars did not perform as well as the 9.115-micron lidar due to degradations from shot noise, wavefront mismatch, refractive turbulence, and atmospheric extinction.

Estes, S. L., Kock, M. E., Lunsford, C. R. and Mendolia, A. S.

"WAKE TURBULENCE AVOIDANCE AUTOMATION: EVALUATION OF FEASIBILITY AND IMPACT"

IEEE/AIAA 30th Digital Avionic Systems Conference, Paper 6A6, October 2011, Seattle,WA.

Wake turbulence encounters are a significant concern to pilots flying in the National Airspace System. By increasing efficiency and capacity, there will be a corresponding reduction in required separations that exist in operations today. As operations are optimized and these separations are reduced, it is important that there is not an increase in wake encounter rates that would tend to limit the acceptance of the FAA's Next Generation Air Transportation System (NextGen). NextGen technology, however, may enable the community to provide better tools to pilots and controllers for avoiding wake, thereby bounding the wake encounter rate at no more than today's operationally acceptable level. In this paper, arrival and departure procedures that take advantage of Automatic Dependent Surveillance-Broadcast and Cockpit Display of Traffic Information technology in the cockpit are reviewed and their performance during a human-in-the-loop evaluation discussed.

Evans, J. E.

"GETTING TO OPERATIONAL DEPLOYMENT: LESSONS FROM TDWR AND ITWS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 520-532

Achieving an operationally useful reliable production system at major airports will be a significant challenge for the AVOSS developers. The FAA experience at developing fully automated aviation weather information systems such as TDWR and the Integrated Terminal Weather System (ITWS) is quite applicable given the many similarities between the systems. A key factor in the FAA aviation system developments has been the operational use of functional 'rapid prototypes' to clarify user needs, quantify and improve benefits, build operational users support and reduce the production system schedule, cost and risk. The AVOSS also needs to get entrained into the FAA acquisition process in the relatively near future if the potential benefits are to be achieved by 2005.

Evans, J. E. and Welch, J. D.

"ROLE OF FAA/NWS TERMINAL WEATHER SENSORS AND TERMINAL AIR TRAFFIC AUTOMATION IN PROVIDING A VORTEX ADVISORY SERVICE"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 24-1 - 24-22

Existing and planned FAA/NWS terminal weather sensors and weather information systems are expected to provide an adequate sensory basis for a useful wake vortex advisory service (WVAS). These meteorological sensors, which provide broad terminal area coverage, should make it possible to reliably estimate and forecast when wake vortex advection characteristics make it possible to reduce the spacings between aircraft on final approach. Effective operational use of such a weather adaptive WVAS would be very difficult without computerized scheduling and spacing aids for terminal air traffic controllers. The developmental Terminal Air Traffic Control Automation (TATCA) program will provide precisely the planning and spacing tools necessary to help controllers take advantage of wake vortex advisories and forecasts to improve terminal throughput and efficiency.

Evans, J. E., Dasey, T. J., Rhoda, D. A., Cole, R. E., Wilson, F. W. and Williams, E. R.

"WEATHER SENSING AND DATA FUSION TO IMPROVE SAFETY AND REDUCE DELAYS AT MAJOR WEST COAST AIRPORTS"

Project Report ATC-290, November 1999, Lincoln Laboratory, Lexington, MA.

The objective of this study was to analyze the weather sensing and data fusion required to improve safety and reduce delays at several west coast airports that are not currently scheduled to receive an Integrated Terminal Weather System (ITWS). This report considers the Los Angeles (LAX), San Francisco (SFO), Seattle (SEA) and Portland, OR (PDX) international airports. Several visits were made to the various ATC facilities to better understand their weather decision support operational needs. Analyses were made of an incident of lightning strikes to two aircraft at SEA in February 1999, and a prototype terminal winds product was developed for LAX that uses profilers as well as plane reports to update the National Weather Service (NWS) Rapid Update Cycle (RUC) winds estimates. We found that an augmented ITWS could potentially address concerns for triggered lightning strikes and vertical wind shear in winter storms at Portland and Seattle. An augmented ITWS terminal winds product (that uses wind profiler data in addition to the current ITWS sensors) could provide very large delay reductions for LAX and SFO during winter storms as a component of a wake vortex advisory system. This augmented product also could provide significant delay reduction benefits at SEA. The sensors required to obtain the projected benefits at SFO do not exist currently. Portland may warrant additional sensors to address the vertical wind shear problems, and LAX would require additional sensors for a wake vortex advisory system. We recommend near-term experimental measurements at PDX to determine the optimum sensor mix and that an operational evaluation of the prototype ITWS terminal winds product be carried out at LAX to determine if the current sensor mix can meet operational needs. Lightning strike data at SEA and PDX should be analyzed to determine if a proposed triggered lightning predicant is accurate.

Evans, P. F. and Hackett, J. E.

"NUMERICAL STUDIES OF THREE-DIMENSIONAL BREAKDOWN IN TRAILING VORTEX WAKES"

NASA CR-137888, June 1976, Lockheed-Georgia Co., Marietta, GA

Finite element, three-dimensional relaxation methods are used to calculate the development of vortex wakes behind aircraft for a considerable downstream distance. The inclusion of a self-induction term in the solution, dependent upon local curvature and vortex core radius, permits calculation of finite lifetimes for systems for which infinite life would be predicted two-dimensionally. The present report describes the associated computer program together with single-pair, twin-pair, and multiple-pair studies carried out using it. It is found, in single-pair studies, that there is a lower limit to the wavelengths at which the 'Crow'-type of instability can occur. Below this limit, self-induction effects cause the plane of the disturbance waves to rotate counter to the vortex direction. Self-induction in two dimensionally generated twin spiral waves causes an increase in axial length which becomes more marked with decreasing initial wavelength. The time taken for vortex convergence toward the center plane is correspondingly increased. The limited parametric twin-pair study performed suggests that time-to-converge increases with increasing flap span. Limited studies of Boeing 747 configurations show correct qualitative response to removal of the outer flap and to gear deployment, as compared with wind tunnel and flight test experience.

Evett, R. C., Jagodnick, A. J. and Zimmer, J. T.

"SIGNAL PROCESSING AND DISPLAY INTERFACE STUDIES"

NAS-8-29822, September 1975, Raytheon Company, Sudbury, MA

The report discusses the principles of operation and the design and testing of a digital signal processor to be used with a laser system in the detection and tracking of vortices. The processor is basically a spectrum analyzer with thresholding, frequency and time integration, and outputs to recorders and computer interfaces.

Extance, L. J., Byres, R., Kilner, C. and McAleese, P.

"AN ANALYSIS OF WAKE VORTEX ENCOUNTERS REPORTED DURING 1996"

R&D Report 9738, September 1997, National Air Traffic Services Ltd., London, England

This report provides a statistical review of the wake vortex encounters which were reported to the Department of ATM Systems Research in the period 1st January 1996 to 31st December 1996. This review provides information to support research and development activity being undertaken to ensure that Air Traffic Control procedures afford protection against the hazard of wake vortices, without unduly constraining airport capacity. There were 151 suspected wake vortex encounters reported. This is 36% higher than the average number of encounters reported for the previous four-year period. The trend indicates an increasing frequency of reported wake vortex encounters for inbound traffic at Heathrow and Gatwick. Analysis of the 151 suspected wake vortex encounters revealed that 12 were probably not due to wake vortex. Of the remaining 139 probable wake vortex encounters, 113 occurred at Heathrow.

Eyink, G. L.

"TURBULENT CASCADE OF CIRCULATIONS"

Comptes Rendus Physique, Vol. 7, Issue 3-4, April-May 2006, pp. 449-455

The circulation around any closed loop is a Lagrangian invariant for classical, smooth solutions of the incompressible Euler equations in any number of space dimensions. However, singular solutions relevant to turbulent flows need not preserve the classical integrals of motion. Here we generalize the Kelvin theorem on conservation of circulations to distributional solutions of Euler and give necessary conditions for the anomalous dissipation of circulations. We discuss the important role of Kelvin's theorem in turbulent vortex-stretching dynamics and conjecture a version of the theorem which may apply to suitable singular solutions.

Fabre, D. and Jacquin, L.

"STABILITY OF A FOUR-VORTEX AIRCRAFT WAKE MODEL"

Physics of Fluids, Vol. 12, No. 10, October 2000, pp. 2438-2443

The stability of an aircraft wake model composed of an external vortex pair (modeling the wing tip vortices) and an internal vortex pair rotating in the opposite direction (modeling the vortices generated by the fuselage and the horizontal tail) in a stationary configuration is investigated with the vortex filament stability method used by Crow [AIAA J., 8, 2172 (1970)] and Crouch [J. Fluid Mech., 350, 311 (1997)]. It is shown that this configuration is unstable with respect to two-dimensional and three-dimensional disturbances. For long wavelength three-dimensional symmetric perturbations, the rapid growth observed in the numerical simulations of Rennich and Lele [J. Aircraft, 36, 398 (1999)] is found. Moreover, the analysis allows one to show that without an excitation of the long-wave mode, the system will naturally develop short wavelength instabilities localized within the inner vortices which do not affect the outer vortices. Inspection of the initial value problem shows that the long-wave modes can be efficiently initiated by the introduction of perturbations on the internal vortices.

Fabre, D. and Jacquin, L.

"SHORT-WAVE COOPERATIVE INSTABILITIES IN REPRESENTATIVE AIRCRAFT VORTICES"

Physics of Fluids, Vol. 16, No. 5, May 2004, pp. 1366-1378

This paper considers the short-wave cooperative instabilities in a family of vortices representative of aircraft wakes. These vortices are characterized by two core scales, an internal core scale and an external core scale and their azimuthal velocity follows a power law in the intermediate zone. The results are compared to the cases of the Rankine (constant) and Lamb-Oseen (Gaussian) vortices, and to the elliptic instability theory. The unstable wavelengths and the structure of the unstable modes are characterized as functions of the base flow parameters. The wavelength of the instability is of the

order of the internal scale and the unstable modes only affect the internal core. In this case the growth rate of the instability is in accordance with the predictions of the elliptical instability theory and is a growing function of the ratio of the core scales.

Fabre, D. and Jacquin, L.

"VISCOUS INSTABILITIES IN TRAILING VORTICES AT LARGE SWIRL NUMBERS"

J. Fluid Mech., Vol. 500, 2004, pp. 239-262

This paper deals with the temporal stability of the q -vortex trailing line vortex model. We describe a family of viscous instabilities existing in a range of parameters which is usually assumed to be stable, namely large swirl parameters ($q > 1.5$) and large Reynolds numbers. These instabilities affect negative azimuthal wavenumbers ($m < 0$) and take the form of center-modes (i.e. with a structure concentrated along the vortex centerline). They are related to a family of viscous modes described by Stewartson, Ng and Brown (1988) in swirling Poiseuille flow, and are the temporal counterparts of weakly amplified spatial modes recently computed by Olendraru and Sellier (2002). These instabilities are studied numerically using an original and highly accurate Chebyshev collocation method, which allows a mapping of the unstable regions up to Re about 1,000,000 and q about 7. Our results indicate that in the limit of very large Reynolds numbers, trailing vortices are affected by this kind of instability whatever the value of the swirl number.

Fabre, D. and Le Dizes, S.

"VISCOUS AND INVISCID CENTRE MODES IN THE LINEAR STABILITY OF VORTICES: THE VICINITY OF THE NEUTRAL CURVES"

Journal of Fluid Mechanics, Vol. 603, 2008, pp. 1-38.

In a previous paper, we have demonstrated that if the Reynolds number is sufficiently large, all trailing vortices with non-zero rotation rate and non-constant axial velocity become linearly unstable with respect to a class of viscous center modes. We provided an asymptotic description of these modes which applies away from the neutral curves in the (q,k) -plane, where q is the swirl number which compares the azimuthal and axial velocities, and k is the axial wavenumber. In this paper, we complete the asymptotic description of these modes for general vortex flows by considering the vicinity of the neutral curves. Five different regions of the neutral curves are successively considered. In each region, the stability equations are reduced to a generic form which is solved numerically. The study permits us to predict the location of all branches of the neutral curve (except for a portion of the upper neutral curve where it is shown that near-neutral modes are not center modes). We also show that four other families of center modes exist in the vicinity of the neutral curves. Two of them are viscous damped modes and were also previously described. The third family corresponds to stable modes of an inviscid nature which exist outside of the unstable region. The modes of the fourth family are also of an inviscid nature, but their structure is singular owing to the presence of a critical point. These modes are unstable, but much less amplified than unstable viscous center modes. It is observed that in all the

regions of the neutral curve, the five families of center modes exchange their identity in a very intricate way. For the q vortex model, the asymptotic results are compared to numerical results, and a good agreement is demonstrated for all the regions of the neutral curve. Finally, the case of 'pure vortices' without axial flow is also considered in a similar way. In this case, center modes exist only in the long-wave limit, and are always stable. A comparison with numerical results is performed for the Lamb-Oseen vortex.

Fabre, D., Cossu, C. and Jacquin, L.

"ABSOLUTE/CONVECTIVE INSTABILITIES AND SPATIAL GROWTH IN A VORTEX PAIR"

Lecture Notes in Physics, Vol. 555, 2000, pp. 162-172

Airplane trailing vortices have a destabilizing effect on ensuing aircraft. Security spacings, related to the trailing vortices 'lifetime' are enforced between take-offs and landings. This spacing limits the maximum takeoff and landing frequency in saturated airports. A number of studies have been devoted to the understanding of vortex wake dynamics, usually modeled by a pair of counter-rotating vortices. Two types of vortex pair three-dimensional instabilities have been identified in the past: a long-wave instability (of the order of the spacing b between the two vortices) and a short-wave instability (of the order of the vortex core radius a). These two mechanisms, which are thought to participate in the vortex wake dissipation, have been observed in recent experiments. One possible technique to accelerate the dissipation of aircraft wakes is to force these instabilities by on-board control devices. Until now only temporal vortex pair instability analyses are available. If one wants to force these instabilities, however, it would be more appropriate to analyze their spatial stability in the airplane reference frame. As the spatial analysis makes sense only when the instabilities are convective, an absolute/convective stability analysis is required. The results presented consist of the absolute/convective and spatial stability analyses of both long- and short-wave instabilities.

Fabre, D., Cossu, C. and Jacquin, L.

"SPATIO-TEMPORAL DEVELOPMENT OF THE LONG AND THE SHORT-WAVE VORTEX-PAIR INSTABILITIES"

Physics of Fluids, Vol. 12, No. 5, May 2000, pp. 1247-1250

We consider the spatio-temporal development of the long-wave and short-wave instabilities in a pair of counter-rotating vortices in the presence of a uniform axial advection velocity. The stability properties depend upon the aspect ratio a/b of the vortex pair, where a is the core radius of the vortices and b their separation, and upon W_o/U_o the ratio between the self-induced velocity of the pair and the axial advection velocity. For sufficiently small W_o/U_o , the instabilities are convective, but an increase of W_o/U_o may lead to an absolute instability. Near the absolute instability threshold, spatial growth rates are larger than those predicted by temporal stability theory. Considering aeronautical applications, it is shown that instabilities of the type considered in this communication cannot become absolute in far field wakes of high aspect ratio wings.

Fabre, D., Jacquin, L. and Loof, A.

"OPTIMAL PERTURBATIONS IN AN AIRCRAFT WAKE COMPOSED OF FOUR VORTICES"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

We consider the instability properties of a system composed of two vortex pairs, which gives a simple model of the wake of an aircraft in landing or take-off configuration. Such a work may hopefully provide indications about possible strategies for designing wing planforms so as to favor faster decay of the wake. We consider counter-rotating configurations for a wide range of parameters which comprises periodic, divergent and stationary configurations, and compute optimal growths of the perturbations at a fixed distance from the generating aircraft.

Fabre, D., Jacquin, L. and Loof, A.

"OPTIMAL PERTURBATIONS IN A FOUR-VORTEX AIRCRAFT WAKE IN COUNTER-ROTATING CONFIGURATION"

J. Fluid Mechanics, Vol. 451, 2002, pp. 319-328

We consider the instability of two vortex pairs in a counter-rotating configuration. Such configurations model vortex wakes observed behind aircraft with inboard vortices produced at the inboard flap edges and at the tips of the horizontal tail. The instability potential is characterized by an optimal perturbation analysis. This extends the analysis of Fabre & Jacquin (2000) which was restricted to particular stationary configurations, and that of Crouch (1997) which considered co-rotating configurations. A complete mapping of the optimal perturbations is presented. The optimal perturbations grow faster than the Crow (1970) instability. However, they correspond to short-wavelength perturbations mainly affecting the weaker inboard vortices. A possible strategy which consists of forcing a long wavelength is then investigated. Application of both the optimal and the long-wave optimal perturbations to reduction of vortex wake danger is discussed.

Fabre, D., Sipp, D. and Jacquin, L.

"KELVIN WAVES AND THE SINGULAR MODES OF THE LAMB-OSEEN VORTEX"

J. Fluid Mech., Vol. 551, 2006, pp. 235-274

Columnar vortices are known to support a family of waves initially discovered by Lord Kelvin (1880) in the case of the Rankine vortex model. This paper presents an exhaustive cartography of the eigenmodes of a more realistic vortex model, the Lamb-Oseen vortex. Some modes are Kelvin waves related to those existing in the Rankine vortex, while some others are singular damped modes with a completely different nature. Several families are identified and are successively described. For each family, the underlying physical mechanism is explained, and the effect of viscosity is detailed. In the axisymmetric case (with azimuthal wavenumber $m = 0$), all modes are Kelvin waves and weakly affected by viscosity. For helical modes ($m = 1$), four families are identified. The first family, denoted D, corresponds to a particular wave called the displacement wave. The modes of the second family,

denoted C, are called cograde waves, except in the long-wave range where they become center modes and are strongly affected by viscosity. The modes of the third family, denoted V, are retrograde, singular modes which are always strongly damped and do not exist in the inviscid limit. The modes of the last family, denoted L, are regular, counter-rotating waves for short wavelengths, but they become singular damped modes for long wavelengths.

Fabrikant, A.

"PLASMA-HYDRODYNAMIC ANALOGY FOR WAVES AND VORTICES IN SHEAR FLOWS"

Lecture Notes in Physics, Vol. 586, 2002, pp. 192-209

A physical analogy between resonant wave-particle interactions in plasma and in fluid mechanics is considered in details. Numerous examples show that the plasma-hydrodynamical analogy is a powerful tool for classification of known phenomena, clarifying their physical nature, discovering new unexpected effects and inventing new devices. The analogy shows up both in plane parallel and in circular shear flows.

Fabry, E. P.

"3D HOLOGRAPHIC PIV WITH A FORWARD-SCATTERING LASER SHEET AND STEREOSCOPIC ANALYSIS"

Experiments in Fluids, Vol. 24, 1998, pp. 39-46

A new 3D PIV system combining holography and stereoscopic PIV is presented. The double pulsed holographic recording relies on the forward scattering of particles in the laser sheet. The holographic images of the particles are used for a stereoscopic PIV analysis. An imaging system with a right-angle prism is used to acquire a stereoscopic pair of images. The application of the system to the vortex flow from an inclined delta wing shows the prospects and limitations of the technique.

Faddy, J. M.

"FLOW STRUCTURE IN A MODEL OF AIRCRAFT TRAILING VORTICES"

PhD Thesis, April 2005, California Institute of Technology, Pasadena, CA.

We consider a model of incompressible trailing vortices consisting of an array of counter-rotating structures in a doubly periodic domain, infinite in the vertical direction. The two-dimensional vortex array of Mallier and Maslowe is combined with an axial velocity profile chosen proportional to the initial axial vorticity to provide an initial condition for the vortex wake. This base flow is a weak solution of the three component steady Euler equations in two dimensions thus allowing its linear stability properties to be investigated. These are used to interpret several stages in the development of vortex structure observed in fully three-dimensional DNS at Reynolds numbers $(\gamma/2\pi\nu) = O(1000)$. For sufficiently high axial velocity, its effect can be seen, in that each vortex in the linear array first develops helical structures before undergoing a period of relaminarization. At later times the more

slowly growing co-operative elliptical instabilities become apparent; however, the helical structure persists and the observed vortical structures remain coherent for longer periods than in the absence of axial velocity. Using the stretched vortex sub-grid model, large-eddy simulation runs are performed at higher Reynolds numbers and a mixing transition identified at about $Re = 10,000-20,000$. Similar phenomena are observed in these simulations as are seen in the DNS. Next the spatial nature of the true aircraft wake is compared to the temporal approximation commonly employed to simplify the computational complexity of the problem. A model is formulated to account for the average axial pressure gradients that develops in the spatial wake but is absent from the temporal simulation. The model enables jet- and wake-like axial flows to be distinguished and the subtle differences in the ensuing turbulent states investigated. Finally, the model is used to investigate co-rotating vortex merger, the new thrust term providing a mechanism to enhance the axial flow further destabilizing the base flow.

Faddy, J. M. and Pullin, D. I.

"FLOW STRUCTURE IN A MODEL OF AIRCRAFT TRAILING VORTICES"

Physics of Fluids, Vol. 17, 2005, 085106-1 to 085106-17

We consider a model of incompressible trailing vortices consisting of an array of counter-rotating structures in a doubly periodic domain, infinite in the vertical direction. The two-dimensional vortex array of Mallier and Maslowe is combined with an axial velocity profile chosen proportional to the initial axial vorticity to provide an initial condition for the vortex wake. This base flow is a weak solution of the steady Euler equations with three velocity components that are functions of two spatial coordinates, thus allowing its linear stability properties to be investigated. These are used to interpret several stages in the development of vortex structure observed in fully three-dimensional direct numerical simulation (DNS) at Reynolds numbers of $O(1000)$. For sufficiently high axial velocity, its effect can be seen, in that each vortex in the linear array first develops helical structures before undergoing a period of relaminarization. At later times the more slowly growing cooperative elliptical instabilities become apparent, but the helical structure persists and the observed vortical structures remain coherent for longer periods than in the absence of axial velocity. Using the stretched-vortex sub-grid model, large-eddy simulation runs are performed at large Reynolds numbers and a mixing transition identified at about $Re = 1-2 \times 10,000$. Similar phenomena are observed in these simulations as are seen in the DNS.

Faddy, J. M. and Pullin, D. I.

"EVOLUTION OF VORTEX STRUCTURES IN A MODEL OF THE TURBULENT TRAILING VORTEX"

In IUTAM Symposium on Elementary Vortices and Coherent Structures: Significance in Turbulence Dynamics, edited by S. Kida, Springer, The Netherlands, 2006, pp. 259-264.

We present results obtained from a direct numerical simulation for a model of incompressible trailing vortices consisting of an array of counter-rotating vortices and a superposed axial velocity in a doubly-

periodic domain, infinite in the vertical direction. The Reynolds number based on vortex circulation is 1000. It is found that for sufficiently strong axial flow, helical instability modes develop on each vortex. This leads to a decrease in the magnitude of the axial flow and subsequent relaminarization of each vortex. At later times, modes corresponding to the more slowly growing co-operative instability become dominant. These produce their own helical structures followed by the rapid growth of small scales, then vorticity cancellation and decay of the vortex array. In the presence of strong axial flow the helical structure persists and the vortices appear more resistant to the breakdown phenomena than for arrays with no axial flow.

Faddy, J. M. and Pullin, D. I.

"EVOLUTION OF VORTEX STRUCTURES IN A MODEL OF THE TURBULENT TRAILING VORTEX"

Proceedings IUTAM Symposium on Elementary Vortices and Coherent Structures, October 2004, Kyoto, Japan.

We present results obtained from a direct numerical simulation for a model of incompressible trailing vortices consisting of an array of counter-rotating vortices and a superposed axial velocity in a doubly-periodic domain, infinite in the vertical direction. The Reynolds number based on vortex circulation is 1000. It is found that for sufficiently strong axial flow, helical instability modes develop on each vortex. This leads to a decrease in the magnitude of the axial flow and subsequent relaminarization of each vortex. At later times, modes corresponding to the more slowly growing co-operative instability become dominant. These produce their own helical structures followed by the rapid growth of small scales, then vorticity cancellation and decay of the vortex array. In the presence of strong axial flow, the helical structure persists and the vortices appear more resistant to the breakdown phenomena than for arrays with no axial flow.

Faery, Jr., H. F and Marchman, III, J. F.

"EFFECT OF WHITCOMB WINGLETS AND OTHER WINGTIP MODIFICATIONS ON WAKE VORTICES"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 207-216

Experimental studies of the wake vortices generated behind six different wingtip configurations are presented. It is shown that the Whitcomb winglet configuration produces two distinct wingtip vortices, each of approximately 65% less swirl velocity than that produced by a simple rounded-tip configuration. Strong axial velocity deficits are shown to be characteristic of these vortices with reduced maximum swirl velocities.

Faery, Jr., H. F.

"THE EFFECT OF WHITCOMB WINGLETS AND OTHER WINGTIP MODIFICATIONS ON WAKE VORTICES"

Ph.D. Thesis, 1975, Virginia Polytechnic Inst. and State Univ., Blacksburg, VA

Wind tunnel experiments were conducted on six wingtip configurations to determine their wake vortex characteristics. The trailing wingtip vortex was probed by a 1/8-inch diameter five-hole yaw head pressure probe. The vortex tangential and axial velocity profiles are compared at five and twenty chord lengths downstream. The Whitcomb winglet and the upper winglet configuration both produce two distinct vortices of the same rotation. The maximum tangential velocity in each is about 64 percent less than that produced by a conventional wingtip configuration. The lift and drag characteristics of the wingtip configurations are compared. The aerodynamic force effects of the wing on the winglet and the winglet on the wing. The downwash distribution on the wing both with and without winglets, and the effect of different winglet dihedral angles on the wing downwash pattern are discussed.

Fage, A. and Simmons, L. F.

"AN INVESTIGATION OF THE AIR-FLOW PATTERN IN THE WAKE OF AN AEROFOIL OF FINITE SPAN"

Proc. Royal Soc. (London), Vol. 225, No. A632, December 1925, pp. 303-330

By means of precise measurements of the wind speed and direction, a picture of the disturbance behind an airfoil of finite span is presented. Changes in the extent and distribution of the vorticity in the wake as it passes downstream are mapped out. The measured vorticity is considered in relation to the circulation around the airfoil. The work provides an experimental verification of the theoretical relation that the total strength of the vorticity leaving a semi-span of an airfoil, as obtained by integration over a transverse plane close behind the airfoil, is equal to the circulation around the median section. It also shows that the distribution of vorticity behind the airfoil is closely connected with the distribution of lift along the span.

Fahey, T., Wilson, E. N., O'Loughlin, R., Thomas, M. and Klipfel, S.

"A HISTORY OF WEATHER REPORTING FROM AIRCRAFT AND TURBULENCE FORECASTING FOR COMMERCIAL AVIATION"

In *Aviation Turbulence*, edited by R. Sharman and T. Lane, Chapter 2, 2016, Springer International Publishing Switzerland, pp. 31-58.

Manual pilot reporting of weather conditions, including turbulence, has been standard procedure during most of the Twentieth century. By the late 1940s, the International Civil Aviation Organization (ICAO) had developed standards which included aircraft-based weather observations by pilots and subsequent government distribution. In the USA, commercial airlines developed their own collection and distribution methods. This was in response to Federal Aviation Administration (FAA) requirements that pilots should report hazardous weather, and airlines should have the ability to monitor the progress of every flight. By the 1980s, flight location as well as wind and temperature were being automatically reported in some areas of the world. But automated turbulence report capability was mainly a research effort with some operational capability during the 1990s and 2000s. Aviation

weather forecasting has seen many government as well as airline efforts over the last 80-100 years. By World War II, military aircraft such as the B-17 were able to reach altitudes of over 30,000 ft. This initiated the need for weather forecasting in the upper troposphere and lower stratosphere. Turbulence and mountain wave forecasting emphasis increased significantly with the transition from propeller to jet powered commercial passenger aircraft in the 1950s and 1960s. By the 2000s, government developed forecasting tools such as the Graphical Turbulence Guidance (GTG) had begun to mature, and airlines continued to focus on minimizing turbulence exposure for passenger and flight attendant safety as well as comfort. Many US airlines have come and gone, likewise for airline meteorology offices. A brief history of Northwest (NWA), Delta, and Western meteorology; turbulence forecasting, including mountain wave; and the NWA/Delta Turbulence Plot system provide added perspective. Still today, manual and automated aircraft-based weather observations as well as government and airline produced turbulence forecasts are very valuable.

Fail, R. A. and Eyre, R. C. W.

"DOWNWASH MEASUREMENTS BEHIND A 12-FT DIAMETER HELICOPTER ROTOR IN THE 24-FT WIND TUNNEL"

Tech. Note 2810, Royal Aircraft Establishment, UK, Sept. 1949.

Some measurements of downwash have been made in a plane behind a 12-ft diameter helicopter rotor over a range of shaft inclination and tip speed ratio. In the various operating conditions, the tunnel tests are in reasonable agreement with the theoretical results for the appropriate type of loading.

Faler, J. H. and Leibovich, S.

"DISRUPTED STATES OF VORTEX FLOW AND VORTEX BREAKDOWN"

Phys. Fluids, Vol. 20, No. 9, September 1977, pp. 1385-1400

Flow visualization studies and laser Doppler anemometer measurements on swirling water flows reveal six distinct types of very large amplitude disturbance modes of the vortex core. Three, the 'axisymmetric' and spiral vortex breakdowns and the 'double helix' have been described by others. A definite order of evolution in parameter space (Reynolds number and circulations) occurs, and is described. Puzzling responses of the axisymmetric and spiral vortex breakdowns to imposed flow transients reported previously are confirmed here, and are traced to the shedding of starting and stopping vortices from swirl vanes. Conclusions bearing upon the validity of some theories of vortex breakdown are possible from the data.

Falissard, F., Lerat, A. and Sides, J.

"VORTICITY PRESERVING SCHEME FOR UNSTEADY COMPRESSIBLE FLOWS"

4th International Conference on CFD (ICCFD), July 10-14, 2006, Ghent, Belgium

Taking advantage of the notion of vorticity preserving schemes introduced by Morton and Roe for acoustics, and on the residual-based schemes family proposed by Lerat and Corre, an implicit second order accurate residual-based vorticity preserving scheme is presented and applied to blade vortex interaction.

Falkner, V. M.

"THE SCOPE AND ACCURACY OF VORTEX LATTICE THEORY"

ARC Technical Report R&M 2740, 1952, Aeronautical Research Council, Great Britain

The report gives an outline of the development of the principles on which potential problems in lifting-plane theory are solved using a vortex lattice for the purpose of computing downwash. The conditions of convergence necessary for an accurate solution are defined, and the main purpose of the report is to show that those connected with the lattice have been, or can easily be satisfied. Published solutions by this method have been mainly concerned with spanwise load grading and local aerodynamic center and examples are given here of earlier checks on accuracy for rectangular and triangular wings, and a yawed infinite wing, based either on an alteration of the lattice spacing or on comparison with downwash obtained by surface integrals. The study of accuracy is now advanced by a comparison based on exact values calculated from surface integrals given by W. P. Jones, and applied to a rectangular and a sweptback wing. The downwashes obtained from the lattice are shown to converge to the exact values, but by a comparison of two solutions for the sweptback wing it is shown that the beneficial coupling effect of the lattice makes it unnecessary to obtain individual downwash values to great accuracy, at least for spanwise load grading and aerodynamic center calculations. Trial calculations reveal that there would be no difficulty in extending the convergence to detailed pressure distribution or other properties of any thin wing, but it is desirable to give prior attention to the main effects of wing thickness and viscosity.

Fan, M. and Steinhoff, J.

"COMPUTATION OF BLUNT BODY WAKE FLOW BY VORTICITY CONFINEMENT"

AIAA Paper No. 2004-0592, Reno, NV, January 2004

A new, fully conservative version of a method, 'Vorticity Confinement' (VC), is used to treat flow over blunt bodies, including attached and separating boundary layers, and resulting turbulent wakes. The method has been developed independently. However, in terms of current computational schemes, it can be described as a rotationally invariant generalization to multiple dimensions of current 1-D discontinuity confinement schemes. The method allows small (order of grid cell) vortical structures to be simulated which would ordinarily be lost due to diffusive and dispersive numerical effects in conventional pde-based finite difference approximations. In addition to small scales, this method is also efficient for large scales since it approximates conventional CFD for them. The basic idea is that an intrinsically discrete, nonlinear term is used to create what are, effectively, solitary wave-like vortical

features at the smallest scales (1-2 cells) that 'live' on the grid lattice, convecting over arbitrary distances with no numerical spreading. The method has been shown to be very effective at treating isolated, thin convecting vortex filaments and bound vortical layers (boundary layers on surfaces) 'immersed' in coarse, uniform Cartesian grids. These boundary layers are automatically captured, or 'immersed' with the method without complex logic, while maintaining no-slip conditions at the surface to allow separation. Results in 3-D are shown for circular cylinder, a sphere, and a half-sphere shell, as well as comparisons with available data.

Fan, Z.

"A COMPUTER MODEL TO PREDICT POTENTIAL WAKE TURBULENCE ENCOUNTERS IN THE NATIONAL AIRSPACE SYSTEM"

PhD Thesis, December 2014, Virginia Polytechnic Institute and State University, Blacksburg, VA.

With an increasing population of super heavy aircraft operating in the National Airspace System and with the introduction of NextGen technologies, the wake vortex problem has become more important for airport capacity and the en-route air traffic operations. The vortices generated by heavy and super heavy aircraft can generate potential hazards to other aircraft on nearby flight paths. Moreover, the design of new airport procedures needs to consider the interactions between aircraft in closer paths. New methods and models are required to examine these effects before new operations are conducted in the National Airspace System (NAS). Reducing wake vortex separations to safe levels between successive aircraft is essential for NextGen operations. One approach taken recently by ICAO and the FAA is to introduce a re-categorization (ReCat) of wake vortex separations to six groups from the existing five groups employed by the FAA in the United States. Reduced aircraft separations can increase capacity in the NAS with corresponding savings in delay times at busy airports. Future NextGen operations are likely to introduce smaller aircraft separations in the en-route and in the terminal area. Such operations would require better methods to identify potential wake hazards from reduced separation operations. This dissertation describes a model to identify potential wake encounters in the future NAS. The goal of the dissertation is to describe the Enhanced Wake Encounter Model (EWEM), a model that employs a detailed NASA-developed wake model to generate wake zones for different aircraft categories under different flight conditions that can be used with aircraft flight path data to identify potential wake encounters. The main contribution of this model is to gain an understanding of potential wake encounters under future NAS operations.

Fan, Z., Schroeder, N., Swol, D. and Trani, A.

"POTENTIAL WAKE TURBULENCE ENCOUNTERS ANALYSIS IN CURRENT AND NEXTGEN FLIGHT OPERATIONS"

Integrated Communications, Navigation and Surveillance Conference (ICNS), April 2013, Herndon, VA, pp. M5-1 - M5-7.

Reducing wake vortex separations to safe levels between successive aircraft is essential for NextGen operations. One approach taken recently by ICAO and the FAA is to introduce a re-categorization of wake vortex separations to six groups from the existing five groups employed by the FAA in the United States. Reduced aircraft separations can increase capacity in the NAS with corresponding savings in delay times at busy airports. Future NextGen operations are likely to introduce smaller aircraft separations in the enroute and in the terminal area. Such operations would require better methods to identify potential wake hazards from reduced separation operations. This paper describes a simulation-based approach to identify potential wake encounters in the future NAS. The goal of the paper is to describe the Wake Encounter Model, a model that employs a detailed NASA-developed wake model to generate wake zones for different aircraft categories under different flight conditions that can be used with aircraft flight path data to identify potential wake encounters. The main contribution of this model is to gain an understanding of potential wake encounters under future NAS operations.

Fantauzzi, M., Delisi, D. P., Pruis, M. J., Lai, D. Y. and Jacob, D.

"WAKE VORTEX COLLECTION AT THE DUBAI INTERNATIONAL AIRPORT AND SAMPLE RESULTS"

AIAA Paper 2016-3436, June 2016, Washington, DC.

The Dubai Air Navigation Services (DANS) has an on-going field experiment at the Dubai International Airport (DXB) to measure wake turbulence generated by aircraft in the In Ground Effect and Out of Ground Effect regions. The data are collected using three Lockheed Martin Coherent Technologies (LMCT) WTX WindTracer pulsed Doppler lidars. The data have been collected from August, 2013, and the data collection is still ongoing. These data are being used to determine vortex circulation decay and vortex position under a variety of atmospheric conditions. The ultimate goal is to safely reduce aircraft separations and to safely increase the capacity of the Dubai International Airport. This paper will outline the strategy behind the lidar placement and the data that are being collected, and will provide a first look at results from the data collection.

Fanucci, A. L. and Jimenez, J. J.

"A NEAR-FIELD COMPARISON OF THE VORTEX-WAKE CHARACTERISTICS OF A TRAPEZOIDAL WING AND A CRANK-ARROW WING"

Report, Aero 16.622 Spring 2003, May 2003, MIT, Cambridge, MA.

Large commercial aircraft produce dangerous wake-vortices. If a trailing aircraft encounters such a vortex before its strength is sufficiently dissipated, the aircraft can experience loss of control authority. The FAA has issued separation standards for all aircraft classes in order to avoid the effects of these wake-vortices. However, these standards are based on the wake-vortex characteristics of conventional, subsonic-cruise aircraft that have trapezoidal wings. The current standards have no mention of crank-arrow wing geometry. In addition, studies have not been done on the wake-vortices of crank-arrow wings.

Fares, E., Huppertz, G., Abstiens, R. and Schroder, W.

"NUMERICAL AND EXPERIMENTAL INVESTIGATION OF THE INTERACTION OF WINGTIP VORTICES AND ENGINE JETS IN THE NEAR FIELD"

AIAA Paper No. 2002-0403, Reno, NV, January 2002

The near wake of a rectangular wing/engine configuration is investigated using numerical simulations and PIV measurements. The analysis is focused on the interaction of the engine jet and the wing-tip vortex in the near wake. The essential details of the solution technique such as turbulence modeling, boundary conditions, and the experimental setup are presented first. The engine jet is experimentally generated by a jet apparatus and simulated numerically using artificial boundaries within the engine. The paper concentrates on the influence of the engine jet on the development of the wing-tip vortex at varying thrust and engine positions. Finally, physical aspects of the flow in the near field behind the wing are discussed and compared with experimental data.

Fares, E., Meinke, M. and Schroeder, W.

"NUMERICAL SIMULATION OF THE INTERACTION OF WINGTIP VORTICES AND ENGINE JETS IN THE NEAR FIELD"

AIAA Paper No. 2000-2222, Denver, CO, June 2000

The near wake of a wing/engine configuration is investigated with the help of numerical simulations. The focus is put on the interaction of the engine jet and the wingtip vortex in the near wake. The essential details of the solution technique such as grid generation, turbulence modeling, boundary conditions, and their implementation are presented first. A modification of the Spalart-Allmaras one-equation model is proposed including a determination of the wall distance with a partial differential equation. The methods are validated with solutions for an isolated analytical vortex and a near wake of a flapped wing based on experimentally determined inflow boundary conditions. Finally, physical aspects of the flow in the near wake of the wing are discussed.

Farlow, N. H., Watson, V. R., Loewenstein, M., Chan, K., Hoshizaki, H., Conti, R. J. and Meyer, J. W.

"MEASUREMENTS OF SUPERSONIC JET AIRCRAFT WAKES IN THE STRATOSPHERE"

International Conference on the Environmental Impact of Aerospace Operations in the High Atmosphere, American Meteorological Society, July 1974, pp. 53-58

Progress is reported in an experimental program consisting of making supersonic aircraft wakes visible in the stratosphere so that photographs can be taken which yield wake dimensions vs time, and so that aircraft equipped with instruments which measure key exhaust species can find and penetrate the wakes. The object is to provide verification of fluid dynamic and chemical models. Three available models are summarized, and the experimental methods used are described. The Lockheed model predictions correspond in general most closely to experimental wake cross-sectional area. NO data are in reasonable agreement with NO predictions, but chemical models are relatively undeveloped, and

additional measurements of exhaust products are needed before verification of chemical models becomes possible. However, the overall feasibility of wake visualization for model verification is substantiated. It is emphasized that significant model differences exist that must be resolved before reliable predictions can be made in the wake regimes studied.

Favier, B., Godeferd, F. S. and Cambon, C.

"MODELING THE FAR-FIELD ACOUSTIC EMISSION OF ROTATING TURBULENCE"

Journal of Turbulence, Vol. 9, No. 30, 2008, pp. 1-21.

This paper focuses on the evaluation of the acoustic emission of anisotropic homogeneous turbulence. We propose a synthetic model that contains the main features of turbulence submitted to rotation: the velocity fluctuations are a mix of random Fourier modes and inertial waves, with variable respective intensities. The acoustic analogy introduced by Lighthill is applied to these sources to estimate the acoustic emission properties of the incompressible anisotropic field, such as the acoustic spectrum and the sound directivity. These quantities are compared to those obtained in the isotropic case, and discussed in view of the available analytical laws for sound emission by isotropic turbulence. An approach based on turbulent sources computed by direct numerical simulations, computationally more expensive than the kinematic sources, is also used for comparison.

Favier, D. P., Lee, S. C. and Maresca, C. A.

"VORTICITY METER CALIBRATION USING A CROSS-WIRES SURVEY"

Experimenta in Fluids, Vol. 2, 1984, pp. 105-111.

A vorticity meter of the vane-type has been used in this study for direct and quantitative measurements of vortical flows. The vane calibration procedure is carried out by using measurements deduced from a preliminary cross-wires survey of the flow field generated in the wake of a half wing set at incidence in the wind tunnel. Emphasis is placed on the resulting calibration law which relates the vane rotational speed to the fluid angular velocity. Specially it is shown that this calibration law can be obtained as a linear expression by considering the minimum threshold rotational speed necessary for vane rotation. When comparing vorticity distributions obtained through the vortical wing wake by the indirect cross-wires technique, good agreements are found with the corresponding vorticity distributions as deduced from the so calibrated vorticity meter.

Favier, D., Maresca, C., Castex, A. and Barbi, C.

"VORTEX INFLUENCE ON OSCILLATING AIRFOILS AT HIGH ANGLE OF ATTACK"

J. Aircraft, Vol. 24, No. 7, July 1987, pp. 424-432

The influence of a streamwise vortical flow on an oscillating airfoil is investigated in a low subsonic wind tunnel. It constitutes a limiting case of more complex practical flow configurations encountered,

for instance, on a rotating helicopter blade section interacting with the vortical wakes generated upstream by the blade tips. The present experimental simulation is realized by means of a semispan airfoil generating a tip vortex convected downstream and nearby the lower side of a second airfoil, which spans the entire test section and oscillates in force-and-aft motion. Steady and unsteady behavior is obtained from lift, drag, and pitching-moment measurements, and chordwise pressure and skin-friction distributions are performed on the oscillating airfoil. Particular attention is given to the interaction effect of the lifting surface on the path and strength of the impinging vortex.

Fay, J. A.

"BUOYANT PLUMES AND WAKES"

Annual Review Fluid Mechanics, Vol. 5, Annual Reviews Inc., Palo Alto, CA, 1973, pp. 151-160

A review is given of the theories of the motion of buoyant plumes and the dispersion of exhaust gases in vehicular and aircraft wakes. Models for estimating the effects of downwash on the growth of buoyant aircraft trails are presented.

Fedorchenko, A. T.

"ON SOME FUNDAMENTAL FLAWS IN PRESENT AEROACOUSTIC THEORY"

Journal of Sound and Vibration, Vol. 232, No. 4, 2000, pp. 719-782.

A critical analysis of the main theoretical approaches to the theory of aerodynamic sound is presented for the case of inviscid gas flow. Various systems of acoustic equations are considered, with and without externally assigned source terms. Decomposition of flow variables into acoustic and non-acoustic components is discussed as a complex problem which is crucial for studying many aeroacoustic phenomena, and a new concept is suggested for this problem. A time-averaging procedure, which is usually applied for such a decomposition, is examined, and its essential flaws are revealed. The general formulation of Lighthill's acoustic analogy is analyzed as well as various subsequent approaches to the theory of sound generation. This analysis shows that in all these the definitions of aerodynamic sound sources are featured by evident defects, and so these models cannot be adopted as physically or mathematically accurate. The relevant problems of experimental and computational research are considered in connection with the theoretical models under discussion.

Feigh, K. M., Sankar, L. and Manivannan, V.

"STATISTICAL DETERMINATION OF VERTICAL RESOLUTION REQUIREMENTS FOR REAL-TIME WAKE-VORTEX PREDICTION"

Journal of Aircraft, Vol. 49, No. 3, May-June 2012, pp. 822-835.

Wake-vortex interaction is one of the primary drivers for aircraft separation minimums. Real-time wake-vortex prediction algorithms could enable following distances to be reduced, improving the

efficiency of the air transport system. This study uses statistical analysis to determine the necessary vertical resolution of meteorological parameters required to enable real-time wake-vortex models to predict wake-vortex position and strength using two separate analyses. The first analysis sought to characterize the accuracy of the predictions of real-time wake-vortex models for 1 m (highest) and 100 m (lowest) resolution by comparing the predictions to measured wake vortices. Using NASA's AVOSS Prediction Algorithm Suite v4.19 and two data sets collected at Memphis and Dallas-Fort Worth, the results indicate that the range of vortex circulation root-mean-square (RMS) error is [1.5-32.6] m²/s, the range of vortex Y-position RMS error is [0.7-134.5] m, and the range of vortex Z-position error is [1.2-10.1] m. The Y-position error had the largest variation with the maximum deviation exceeding 25 m. The second analysis sought to characterize the precision of the real-time wake-vortex model predictions as the resolution of the input meteorological files was reduced from 1 m to 100 m. Normalized RMS values (by 1 m resolution) were calculated for resolutions of 5, 15, 20, 25, 30, 40, and 100 m averaged over the first 60 s of data available. For predicted circulation, differences were found between medians at input resolutions 5-20 m vs 25-100 m; for Y- and Z-positions, differences were found between medians 100 m and all others.

Feigh, K., Sankar, L., Schrage, D., Huff, B., Flick, A. and Manivannan, V.

"APA SUITE SENSITIVITY STUDY AND MODEL SCORING METHODOLOGIES"

Report DTFWA-09-A-8000, December 2010, Georgia Institute of Technology, Atlanta, GA.

Three methods for scoring wake vortex models have been presented: a residual method, a corridor exit time method, and a cross-correlation method. Each method can provide insight into specific areas of strength and weakness of wake models. The residual method provides the most thorough scoring of model accuracy, as it compares model output point by point with experimental data. Both the APA and TDP methods perform similarly under this method, agreeing with results observed in the sensitivity study performed in Task 1. The corridor exit method also shows very little difference between the methods. Both models produce a very conservative estimate of the vortex exit time from the defined corridor. At a smaller corridor size however, the TDP method significantly under-predicts corridor exit time for heavy aircraft. The cross-correlation method provides a measure of the uncertainty between the measured and predicted data with time. It can be used to align measured and predicted data by finding the lag time with the highest correlation. Under this methodology, the TDP method retained correlation better than the APA method did with time, suggesting that the TDP method is more resistant to changes in circulation and vortex position than the APA method as time goes on.

Felker III, F. F., Piziali, R. A. and Gall, J. K.

"SPANWISE LOADING DISTRIBUTION AND WAKE VELOCITY SURVEYS OF A SEMI-SPAN WING"

NASA Tech. Memorandum 84213, Feb. 1982, US Army Aviation Research and Development Command, Moffett Field, CA (also, USAVRADCOM TR 82-A-1)

The spanwise distribution of bound circulation on a semi-span wing and the flow velocities in its wake were measured in a wind tunnel. Particular attention was given to documenting the flow velocities in and around the developing tip vortex. A two-component laser velocimeter was used to make the velocity measurements. This report presents, without discussion, the spanwise distribution of bound circulation, three components of the time-averaged velocities throughout the near wake and their standard deviations, and the integrated forces and moments on a metric tip as measured by an internal strain gage balance.

Felten, F. N. and Lund, T. S.

"NUMERICAL SIMULATION OF PARALLEL AIRFOIL/VORTEX INTERACTION USING A ZONAL HYBRID RANS/LES METHOD"

AIAA Paper No. 2005-5127, Toronto, Canada, June 2005

Helicopter Blade-Vortex Interaction (BVI) generally occurs under certain conditions of powered descent or during extreme maneuvering. The vibration and acoustic problems associated with the interaction of rotor tip vortices and the following blades is a major aerodynamic concern for the helicopter community. Numerous experimental and computational studies have been performed over the last two decades in order to gain a better understanding of the physical mechanisms involved in BVI. The most severe interaction, in term of generated noise, happens when the vortex filament is parallel to the blade, thus affecting a great portion of it. Most of the previous numerical studies of parallel BVI fall within a potential flow framework therefore precluding vortex-induced flow separation. Some Navier-Stokes approaches using dissipative numerical methods in conjunction with RANS-type turbulence models have also been attempted, but with limited success. In this work, the situation is improved by increasing the fidelity of both the numerical method and the turbulence model. A kinetic energy conserving finite-volume scheme using a collocated-mesh arrangement, specially designed for simulation of turbulence in complex geometries, was implemented. For the turbulence model, a cost-effective zonal hybrid RANS/LES technique is used. The concentrated tip vortex is not attenuated as it is convected downstream and over a NACA-0012 airfoil. The lift, drag, moment coefficients induced by the passage of the vortex are monitored in time and compared with available experimental data.

Ferguson, S. and Dreier, M. E.

"EMPIRICAL WAKE TURBULENCE MODEL OF TILTROTOR AIRCRAFT"

SAE Paper No. 2005-01-3182, Oct. 2005, Grapevine, TX.

This paper describes the methods used to collect and reduce wake turbulence data behind two distinct types of tiltrotor aircraft using a Light Detection and Ranging (LIDAR) measurement system, which uses laser velocimetry to measure the velocity of dust particles in air that has been disturbed by the passage of an aircraft. The test aircraft flew at various combinations of weight, rotor speed, airspeed, and configuration. The MIT LL LIDAR system measured the wake vortices with minimal pre-test preparation; we obtained a large quantity of high-quality data in only a few days of testing. The

data shows tiltrotor and fixed-wing wake characteristics are very similar. Data reduction methods used a classical horseshoe vortex system as a template, and employed a vortex that had a rotational core and an irrotational outer field. Intersecting polynomials that are linear in downstream distance and bi-linear in downstream distance and mast angle adequately modeled vortex strength. A bi-quadratic polynomial function of downstream distance and mast angle adequately modeled core size.

Ferguson, S. W. and Kocurek, J. D.

"ANALYSIS AND RECOMMENDATION OF SEPARATION REQUIREMENTS FOR ROTORCRAFT OPERATION AT AIRPORTS AND HELIPORTS"

TR-1224-1, September 1986, Systems Technology Inc., Mountain View, CA.

Low-speed rotorcraft operations at airports and heliports are investigated to better understand and quantify the potential hazards associated with various types of rotor-wash flow fields. Mathematical models for various types of rotor-induced flow fields are developed. These models are utilized in conjunction with hazard analysis models to evaluate the potential for rotor-wash related accidents in various operational scenarios. Correlation with available flight test and laboratory experimental data is provided wherever possible. The result from the analysis effort is a recommendation of separation requirements for rotorcraft operations at airports and heliports. Recommendations are also provided for future research that would aid in the elimination of safety factors used in the development of recommended separation criteria.

Ferguson, S. W. and Kocurek, J. D.

"ROTORWASH COMPUTER MODEL -- USER'S GUIDE"

DOT/FAA/RD-90/25, November 1991, Computational Methodology Associates, Hurst, TX.

The user's guide for the Rotorwash (ROTWASH) Analysis program is documented in this report. This computer program is used to analyze the rotor wash flow field characteristics and their effect on the environment for rotorcraft in hovering and low speed flight in close proximity to the ground. The documentation provides step-by-step descriptions on the use of each analysis option and a listing of the IBM PC/PC-compatible based FORTRAN-77 software. A brief introductory section to the report describes the history of the ROTWASH analysis software. References for the mathematical models used in the analysis modules are included in the report.

Fernandez, F. L. and Lubard, S. C.

"TURBULENT VORTEX WAKES AND JETS"

AIAA Paper No. 1971-0615, Palo Alto, CA, 1971

The turbulent viscous core of a potential vortex with axial velocity excess or defect is considered. An integral method is used with quasi-cylindrical flow approximations to describe the flow in the core of

the vortex. Models are postulated for both axial and swirl mixing. The resulting equations are shown to possess both regular wake-like and jet-like solutions and solutions which become singular indicating vortex breakdown. The singular solutions are found only for single vortex cores with a net axial momentum deficiency which implies a net drag for the vortex generator.

Fernandez-Feria, R., del Pino, C. and Parras, L.

"VISCOUS INSTABILITIES OF BATCHELOR'S VORTEX FOR HIGH SWIRL NUMBERS; THE ONSET OF ABSOLUTE INSTABILITIES AND NON-PARALLEL EFFECTS"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

Batchelor's vortex has been commonly used in the past as a model for trailing vortices. Using a temporal stability analysis, Fabre and Jacquin have recently found new viscous unstable modes for the high swirl numbers of interest in actual large-aircraft vortices. More recently, these instabilities were characterized asymptotically by Le Dizès and Febre and by Heaton. We look here for these unstable viscous modes occurring at large swirl numbers (q greater than 1.5), and large Reynolds numbers (Re greater than 1000), using a spatial stability analysis, thus characterizing the frequencies at which these modes become convectively unstable for different values of q , Re , and for different intensities of the uniform axial flow. We consider both jet-like and wake-like Batchelor's vortices, and can analyze the stability for Re as high as 100,000,000. We also characterize the frequencies and the swirl numbers for the onset of absolute instabilities of these unstable viscous modes for large q . One of the main conclusions is that these frequencies are not related to those observed experimentally for the vortex meandering phenomenon in trailing vortices. On the other hand, we also analyze the spatial stability of Batchelor's vortex considering non-parallel effects associated to the axial variation of this self-similar vortex that models the far downstream behavior of trailing vortices.

Fernando, H. J. S. and Smith, IV, D. C.

"VORTEX STRUCTURES IN GEOPHYSICAL CONVECTION"

Eur. J. Mech. B - Fluids, Vol. 20, 2001, pp. 437-470

An intriguing variety of vortex structures arise during buoyant convection, especially in the presence of background stratification and rotation. These vortices play an important role in environmental fluid motions, bearing upon small-scale turbulence to planetary-scale circulation. A brief review of vortex motions associated with buoyant convection is presented in this paper, emphasizing the sources of vorticity, evolution of vortex structures and their role in oceanic and atmospheric dynamics. The genesis of a variety of vortices, for example, mushroom vortices, geostrophic and ageostrophic vortices, dipolar structures and hetons in buoyant convection flows is described, and parameterizations to represent their properties are discussed. New laboratory and numerical simulation results on vortex-related phenomena in stratified and rotating fluids and their implications in geophysical convective flows are also presented.

Ferreira de Sousa, P. J. S. A. and Pereira, J. C. F.

"REYNOLDS NUMBER DEPENDENCE OF TWO-DIMENSIONAL LAMINAR CO-ROTATING VORTEX MERGING"

Theoretical and Computational Fluid Dynamics, Vol. 19, 2005, pp. 65-75

The paper reports unsteady Navier-Stokes calculations of laminar two-dimensional co-rotating vortex merging for various Reynolds numbers. The unsteady, incompressible two-dimensional Navier-Stokes equations were solved with fourth-order Runge-Kutta temporal discretization and fourth-order symmetric compact schemes for spatial discretization. Calculations of the unsteady Taylor vortex benchmark showed that fourth-order accurate solutions for all primitive variables were indeed achieved. Calculations for a pair of equal-strength co-rotating vortices show good agreement with reported direct numerical simulation and experiments for the evolution of the separation distance and core radius. It is found that the time required for merging is inversely proportional to the square root of the Reynolds number. According to previous experimental research, it was also found that complete merging in laminar regime undergoes four stages with physical meaning. The physical mechanism responsible for the merging process is investigated and it is found that the antisymmetric vorticity dynamics plays an important role until full merging.

Ferreira de Sousa, P. J. S. A. and Pereira, J. C. F.

"LAMINAR CO-ROTATING BATCHELOR VORTEX MERGING"

Theoretical Computational Fluid Dynamics, Vol. 23, 2009, pp. 1-14.

The dynamics of laminar co-rotating vortex pairs without axial flow have been recently thoroughly studied through theoretical, experimental, and numerical studies, which revealed different instabilities contributing to the decay of the vortices. In this paper, the objective is to extend the analysis to the case of co-rotating vortices with axial flow at low Reynolds numbers. A high-order incompressible Navier-Stokes flow solver is used. The momentum equations are spatially discretized on a staggered mesh by finite differences and all derivatives are evaluated with 10th order compact finite difference schemes with RK-4 temporal discretization. The initial condition is a linear superposition of two co-rotating circular Batchelor vortices with $q = 1$. It is found that there is an initial evolution that resembles the evolution that single $q = 1$ vortices go through. Azimuthal disturbances grow and result in the appearance of large-scale helical sheets of vorticity. With the development of these instability waves, the axial velocity deficit is weakened. The redistribution of both angular and axial momentum between the core and the surroundings drives the vortex core to a more stable configuration, with a higher q value. After these processes, the evolution is somewhat similar to a pair of co-rotating Lamb-Oseen vortices. A three-dimensional instability develops, with a large band of unstable modes, with the most amplified mode corresponding scaling with the vortex initial separation distance.

Ferri, A.

"PRELIMINARY INVESTIGATION OF DOWNWASH FLUCTUATIONS OF A HIGH-ASPECT-RATIO WING IN THE LANGLEY 8-FOOT HIGH-SPEED TUNNEL"

NACA RM No. L6H28b, August 1946, Memorial Aeronautical Laboratory, Langley Field, VA.

A series of tests have been made in the wake of a high-speed wing of high aspect ratio at Mach numbers up to approximately 0.90 to determine the fluctuations of the downwash in the zone of possible tail locations. Serious fluctuations occurred in the wake of the wing. The fluctuations extended beyond the wake boundaries but with decreasing amplitude. For a high angle of attack of the wing (7 deg) and high Mach numbers the fluctuations were very large (3 1/2 deg maximum) and extended as high as approximately 0.90 chord above the chord line of the wing. For medium angles of attack (0, 2, and 4 deg) important fluctuations occurred up to about 0.70 chord above the chord line of the wing.

Ferris, P. D.

"THE FORMATION AND FORECASTING OF CONDENSATION TRAILS BEHIND MODERN AIRCRAFT"

Meteorol. Appl., Vol. 3, 1996, pp. 301-306.

The formation of a condensation trail behind an aircraft gives away its presence. Despite the current use of radar for aircraft detection, contrail formation is still important to military aviation. Seeing a contrail only requires the unaided eye. The theory of contrail formation for a dry environment, using values of engine-dependent variables appropriate to modern jet aircraft, gives values of the critical temperature for contrail formation. These form a line nearly parallel to, but colder than, the MINTRA line on a tephigram. These values though, do not allow for the effect of environmental humidity, which may be significant at the levels where aircraft fly. A new forecasting technique is proposed which involves determining the exact critical temperature value. This can be done using a suitable contrail formation graph or with a tephigram, finding the necessary correction to the MINTRA temperature. If the atmospheric temperature is colder than this critical temperature, a contrail should be forecast to form.

Ferziger, J. H.

"LOW-FREQUENCY ACOUSTIC SCATTERING FROM A TRAILING VORTEX"

J. Acoustical Soc. America, Vol. 56, No. 6, December 1974, pp. 1705-1707

The cross section for the scattering of low-frequency (~ 100 Hz) sound by an aircraft trailing vortex is computed using the Born approximation. The predicted cross section is large enough to permit size and strength measurements. Although precise location of a vortex is better done with high-frequency refraction, a monitoring system based on low-frequency acoustic radar is possible, and a system combining the best features of each is also feasible.

Feuerle, T., Steen, M. and Hecker, P.

"A NEW CONCEPT FOR WAKE VORTEX HAZARD MITIGATION USING ON-BOARD MEASUREMENT EQUIPMENT"

AIAA Paper 2013-4426, August 2013, Los Angeles, CA.

Wake Vortex hazards are a huge threat in aviation. These hazards are well accepted in the vicinity of airports (both departure and arrival). But also enroute a number of incidents had happened in the past. Current wake vortex mitigation strategies are based on static distances (in space and/or time). In future air traffic management concepts of SESAR and NextGen these static distances will be replaced by dynamic separation strategies. Furthermore, concepts for self-separation of aircraft are described. This paper will discuss the work at TU Braunschweig, where a new concept for wake vortex hazard mitigation had been developed. Additionally, TU Braunschweig will install a wind turbulence measurement equipment on-board of its research aircraft. This installation will be also described and the possible usage will be discussed.

Feuerle, T., Steen, M. and Hecker, P.

"NEW CONCEPT FOR WAKE-VORTEX HAZARD MITIGATION USING ONBOARD MEASUREMENT EQUIPMENT"

Journal of Aircraft, Vol. 52, No. 1, January-February 2015, pp. 42-48.

Wake-vortex hazards are a huge threat in aviation. These hazards are well accepted in the vicinity of airports (both departure and arrival). But also a number of enroute incidents have happened in the past. Current wake-vortex mitigation strategies are based on static distances (in space and/or time). In future air traffic management concepts of Single European Sky Air Traffic Management Research and NextGen, these static distances will be replaced by dynamic separation strategies. Furthermore, concepts for self-separation of aircraft are described. This paper will discuss the work at Technische Universitat Braunschweig, where a new concept for wake-vortex hazard mitigation has been developed. The basic idea of the new concept is that only a criticality parameter will be transmitted between aircraft to ensure a safe separation even within new self-separation concepts. The criticality parameter will give an indication about the severity (and therefore criticality to the following aircraft) of the vortices. Additionally, Technische Universitat Braunschweig will install a wind-turbulence measurement equipment onboard its research aircraft. This installation will be also described, and the possible usage will be discussed.

Few, Jr, A. G.

"SOME EFFECTS OF SWEEP AND THICKNESS ON THE EXPERIMENTAL DOWNWASH CHARACTERISTICS AT TRANSONIC SPEEDS OF A SERIES OF HIGHLY TAPERED WINGS WITH AN ASPECT RATIO OF 3, TRANSONIC-BUMP METHOD"

NACA RM L55J12, February 1956, Langley Aeronautical Laboratory, Langley Field, VA.

An investigation by the transonic-bump technique of some effects of sweep and thickness on the transonic downwash and wake characteristics of a series of highly tapered semispan wings with an aspect ratio of 3 has been made in the Langley high-speed 7- by 10-foot tunnel. The Mach number range extended from 0.60 to 1.18 with corresponding Reynolds numbers ranging from about 780,000 to 930,000. The angle-of-attack range was from -2 to about 24 degrees. The measurements of downwash and dynamic pressure were made for a range of vertical distances from the wing chord plane extended, but at only one spanwise station and for a given wing plan form, at only one longitudinal station. Increases in wing sweep provided a decrease in the rate of change of downwash with angle of attack in the low angle-of-attack range for all Mach numbers, and provided less variation with Mach number at all distances from the wing chord plane. The rate of change of downwash with angle of attack reached a maximum near the wing chord plane for all wing sweep angles. Above the wing chord plane the rate of change of downwash with angle of attack increased to maximum values exceeding unity with an increase in angle of attack for all conditions of wing sweep and thickness. For a quarter-chord sweep angle of 14.03 degrees a decrease in wing thickness ratio from $t/c = 0.045$ to 0.02 produces increase in the rate of change of downwash with angle of attack at any distance from the wing chord plane extended up to a Mach number of about 1.09. Regardless of wing sweep or thickness, increasing the speed from subsonic to supersonic caused the wake center to be displaced toward the wing chord plane and, although the losses in wake dynamic pressure were reduced, there was a general thickening of the wake in going to supersonic speeds.

Fewings, R.

"ULTRA-HIGH-CAPACITY AIRCRAFT WILL INTENSIFY AIRPORT SAFETY ISSUES"

Airport Operations, Flight Safety Foundation, Vol. 21, No. 1, January-February 1995, pp. 1-7.

The new generation of transports will likely cause further pressures on ground maneuvers and emergency evacuations at airports, and possibility increase wake vortex hazards.

Fidler, J. E.

"APPROXIMATE METHOD FOR ESTIMATING WAKE VORTEX STRENGTH"

AIAA Journal, Vol. 12, No. 5, May 1974, pp. 633-635

An approximate method is presented for estimating the strength of slender-body wake vortices. The method is shown to yield good accuracy for the case of asymmetric vortices in the wake of a body at high angles of attack.

Fiduccia, P.

"NASA CONOPS TEAM AND THE IDENTIFICATION OF REQUIRED DATA TO ESTABLISH SAFETY OF PROPOSED ACTIVE PREDICTION WAKE VORTEX SOLUTIONS"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

This presentation on the NASA Conops Evaluation Team covers the following points: Wake Conops Team Goals and Objectives, Scope; Team Members and Expertise; Candidate Operational Enhancements to be Analyzed by the Evaluation Team; Order of Analysis; Baseline Report Contents; Conops Evaluation Report Contents; Description of Conops for Closely Spaced Parallel Runway Arrivals, dynamic separation based on active wind sensing and prediction; and Comparison of Conops with Related FAA Operational Enhancements. Results to date: Conops Definition and Analysis, Safety Analysis Methodology Selection, Research Issues Identified, and Issues Identified to Decision Makers.

Fiduccia, P. C., Bryant, W. and Lang, S.

"FAA/NASA WAKE TURBULENCE RESEARCH PROGRAM"

Journal of ATC, Vol. 46, No. 1, January-March 2004, pp. 17-21

This is the first of a series of articles on the FAA/NASA Wake Turbulence Research Program (Program) to revise wake turbulence separation standards, procedures, and criteria to increase airport capacity while maintaining or increasing safety. This article introduces the FAA and NASA elements of the Program, provides the status of the FAA Program elements already underway, and describes the Conops Evaluation Team (CET), which supports the planning for NASA's wake research and technology development activities.

Filippone, A.

"DATA AND PERFORMANCES OF SELECTED AIRCRAFT AND ROTORCRAFT"

Progress in Aerospace Sciences, Vol. 36, 2000, pp. 629-654.

The purpose of this article is to provide a synthetic and comparative view of selected aircraft and rotorcraft (nearly 300 of them) from past and present. We report geometric characteristics of wings (wing span, areas, aspect-ratios, sweep angles, dihedral/anhedral angles, thickness ratios at root and tips, taper ratios) and rotor blades (type of rotor, diameter, number of blades, solidity, rpm, tip Mach numbers); aerodynamic data (drag coefficients at zero lift, cruise and maximum absolute glide ratio); performances (wing and disk loadings, maximum absolute Mach number, cruise Mach number, service ceiling, rate of climb, centrifugal acceleration limits, maximum take-off weight, maximum payload, thrust-to-weight ratios). There are additional data on wing types, high-lift devices, noise levels at take-off and landing. The data are presented on tables for each aircraft class. A graphic analysis offers a comparative look at all types of data. Accuracy levels are provided wherever available.

Filippone, A., Bakker, R., Basset, P. M., Rodriguez, B., Green, R., Kutz, B., Bensing, F. and Visingardi, A.

"ROTOR WAKE MODELLING IN GROUND EFFECT CONDITIONS"

37th European Rotorcraft Forum, September 2011, Milano, Italy.

In this contribution we address the nature of helicopter rotor wakes in presence of the ground. We present some problems of helicopter flight on a flat surface, a validation exercise for a hover in ground effect (Light's experiment) and novel experiments on scaled rotor in advancing flight. We present briefly the computational methods used for this validation exercise. The methods range from lifting line to unsteady Reynolds-averaged Navier-Stokes equations. Validations are shown for out-of-ground and various ground clearances.

Filotas, L. T.

"DISTORTION OF A SHOCK WAVE TRAVERSED BY A VORTEX"

Tech. Note No. 96, January 1967, University of Toronto Institute for Aerospace Studies, Toronto, Canada.

A theoretical treatment of the sound field produced upon the interaction of a vortex and a normal shock wave was presented some time ago in UTIA Report No. 61 (Ribner, 1959). The techniques of this analysis are now used to derive expressions for the shape of the distorted shock front. It is found that outside of the section cut off by the cylindrical acoustic wave emanating from the vortex center, the shock remains essentially straight. The portion within this section has curvature, resulting in a finite displacement of the two straight segments. These theoretical predictions are in qualitative agreement with the features noted by experimental investigators of the same phenomenon. As no other presently published theory yields the shock wave shape, this work demonstrates the generality of the approach used.

Finch, R. V.

"VORTEX REDUCING WING TIP"

US Patent 4,108,403, August 1978.

An airfoil tip is constructed to droop downward and extend aft of the trailing edge of the air foil structure and to include air foil configuration both chordwise and spanwise with camber in both the chordwise and spanwise directions and further including a vortex opposing twist in the chordwise direction.

Finck, R. D.

"USAF STABILITY AND CONTROL DATCOM"

AFWAL-TR-83-3048, April 1978, McDonnell Douglas Corporation, Long Beach, CA.

This report is a collection, correlation, codification, and recording of best knowledge, opinion, and judgment in aerodynamic stability and control prediction methods. It presents substantiated techniques for use (1) early in the design or concept study phase, (2) to evaluate changes resulting from proposed engineering fixes, and (3) as a training or cross-training aid. It bridges the gap between theory and practice by including a combination of pertinent discussion and proven practical methods. For any given configuration and flight condition, a complete set of stability and control derivatives can be determined without resort to outside information. A spectrum of methods is presented, ranging from very simple and easily applied techniques to quite accurate and thorough procedures. Comparatively simple methods are presented in complete form, while the more complex methods are often handled by reference to separate treatments. Tables which compare calculated results with test data provide indications of method accuracy. Extensive references to related material are also included.

Findlater, P. A., Greenhill, S. E. and Scott, W. D.

"DESIGN AND TESTING OF A TURBULENCE PROBE FOR HARSH FLOWS"

Environmental Fluid Mechanics, Vol. 1, 2001, pp. 3-28.

The force of wind on the ground created by turbulent eddies is commonly used to describe the horizontal flux of material during wind erosion. Here we present the Murdoch Turbulence Probe, an instrument for use in both clean and eroding flows which uses pressure differences to measure the three components of wind velocity. Correlation techniques calculate the forces near the ground and turbulence statistics in nearly real time, including turbulent velocity fluctuations from less than 0.1 Hz to 200 Hz, mean flow velocities, Reynolds stresses as well as the integral length and time scales. In the portable wind-tunnel used by Agriculture Western Australia, turbulence statistics were recorded over stable surfaces and in blowing sand from the initiation of erosion up to the time the sand supply was exhausted. Estimates of the friction velocity derived from the turbulence probe were compared with estimates obtained from the wind speed profile measured with a rake of pitot and static tubes. The Murdoch Turbulence Probe appears to work well in sandblasting conditions. Relative turbulence intensities ranged from 0.11 to 0.2 and are in close agreement with values in the literature. The ratio of the turbulence to the friction velocity (3 to 3.2) is at the high end of the reported range. The Reynolds stress measurements agree closely with predictions of the threshold friction velocities of the sand and estimates from the wind speed profile with a von Karman constant of about 0.3, lower than the commonly accepted value of 0.4. We suggest that the wind-tunnel profile represents the 'outer layer' of the boundary-layer that may best be described by a 'Wake Law' or 'Defect Law'. At about 54 mm above the surface, the friction velocity decreases from 0.64 m/s to 0.39 m/s and the mean velocity increases from 9.6 m/s to 11.6 m/s as the supply of sand is depleted. In addition to the friction velocity, other scales may be necessary to characterize the overriding effect of the wind and in extending wind-tunnel results to the field.

Fine, N. E. and Kring, D.C.

"OPTO-ACOUSTIC TRACKING OF AIRCRAFT WAKE VORTICES"

AIAA-2005-2965, Monterey, CA, May 2005

Flight Safety Technologies, Inc. is developing an opto-acoustic sensor array called SOCRATES to detect and track the sound generated by the trailing wake vortices created by aircraft. Tracking these aircraft wake vortices during arrival and departure will allow for safer and more efficient airport operations. The sensor array, in essence a type of sonar, employs infrared lasers that act as microphones. This paper describes the sensor array and its ongoing field testing.

Fine, N., Rees, F. and Von Winkle, W.

"ACOUSTIC MEASUREMENTS IN AN AIRPORT ENVIRONMENT AND THE IDENTIFICATION OF THE SOUND RADIATED BY AIRCRAFT WAKE VORTICES"

135th Acoustical Soc. America Conf., Seattle, WA, May 1998

Results are presented of an effort to measure the sound generated by aircraft wake vortices. The objective of the research is to estimate the spectral shape and source levels characteristic of the sound generated by aircraft wakes during approach and landing. Measurements were made at JFK airport in August 1997, for various aircraft, using three Bruel and Kjaer outdoor microphones. The data were recorded to tape, and spectrum analysis was performed using a B&K portable spectrum analyzer. The three microphones were placed near the beginning of runways 13L and 22L, arrayed in several configurations parallel to and perpendicular to the runway centerline. Initial spectrum analysis of the data revealed a prominent broadband 'hump' in the one-third octave sound-pressure level spectra, centered at approximately 50-60 Hz for a B-747 landing (with a band-width of roughly 20-30 Hz). The timing of the hump is consistent with that expected for wake vortex sound and it is hypothesized to be generated by the wake vortices. Cross correlations between microphones arrayed parallel to the runway will test this hypothesis. Additional data, which are to be recorded in January 1998, will also aid in identifying the wake vortex sound characteristics.

Fink, P. T. and Soh, W. K.

"A NEW APPROACH TO ROLL-UP CALCULATIONS OF VORTEX SHEETS"

Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences, Vol. 362, Issue 1709, July 1978, pp. 195-209

Careful discretization of two-dimensional vortex sheets has led to the discovery of the cause of inconsistency of the multi-vortex representation of such sheets. The method described here is applied to the calculation of roll-up of the trailing vortex sheet shed from an elliptically loaded wing. Contrary to the results obtained with multi-vortex methods, calculations are found to converge as the discretization is refined.

Finkelstein, P. L., Kaimal, J. C., Gaynor, J. E., Graves, M. E. and Lockhart, T. J.

"COMPARISON OF WIND MONITORING SYSTEMS. PART II: DOPPLER SODARS"

Journal of Atmospheric and Oceanic Technology, Vol. 3, 1986, pp. 594-604.

Measurements of wind speed, wind direction, and the vertical component of turbulence, from four different commercially available Doppler sodars, are compared with similar measurements from in situ sensors on a 300 m instrumented tower. Results indicate that the four sodars measure wind speed and direction accurately and with reasonably high precision. The sodars tended to overestimate the vertical component of turbulence at night and to underestimate it during the day. Precision in those measurements was considerably poorer than for the averaged speeds and directions. Analysis of the vertical wind speed measurements from the sodars indicates that the measurement inaccuracies arise from a combination of aliasing and spatial averaging. Comparison of five in situ wind systems with a sonic anemometer are presented in Part I of this two-part series of papers.

Finkelstein, P. L., Kaimal, J. C., Gaynor, J. E., Graves, M. E. and Lockhart, T. J.

"COMPARISON OF WIND MONITORING SYSTEMS. PART I: IN SITU SENSORS"

Journal of Atmospheric and Oceanic Technology, Vol. 3, 1986, pp. 583-593.

It has recently become clear through advances in both theoretical and experimental meteorology, that improvements in modeling the transport and dispersion of pollutants will require on-site measurements of the atmosphere. This requirement has in turn generated questions about 1) our ability to make such measurements both near the surface and through the first few hundred meters of the atmosphere and 2) the expected accuracy and precision of such measurements using current technology. To help answer these questions an experiment was conducted at the Boulder Atmospheric Observatory to assess the ability of in situ and remote sensors to measure the mean and turbulent properties of the lower atmosphere. Two categories of sensors were tested. One consisted of lightweight in situ sensors of types that have been frequently used in the recent past for boundary layer studies. The other category consisted of four commercially available Doppler sodars, with the capability to measure wind speed, wind direction, and vertical component of turbulence, at various heights above the ground. Part one of this two-part study deals with comparisons of five in situ wind sensing systems with a three-axis sonic anemometer, all mounted on 10 m towers spaced approximately 5 m apart. Discussed in this paper are statistical measures of their accuracy, precision, and spectral response to fluctuations in the wind.

Finn, L. I. and Boghosian, B. M.

"A GLOBAL VARIATIONAL APPROACH TO VORTEX CORE IDENTIFICATION"

Physica A: Statistical Mechanics and Its Applications, Vol. 362, Issue 1, March 2006, pp. 11-16

We present a global variational definition of a vortex core in three-dimensional flows, and describe its implementation for tracking principal vortex cores in a viscous fluid. Our definition is motivated by the observation that the line integral of vorticity along any path worthy of being called a vortex core is likely to be large. Inverting this observation, we define a vortex core as a curve for which this line integral is a local maximum in the space of all such curves (with appropriate boundary conditions). We present an algorithm by which candidate curves are evolved using a Ginsburg-Landau equation to locate vortex cores. We demonstrate the implementation of this algorithm using initial vorticity fields generated with clearly identifiable vortex cores, and evolved using a lattice Boltzmann Navier-Stokes solver.

Fiorino, F.

"A300 INSPECTIONS LOOM FOLLOWING JFK CRASH"

Aviation Week & Space Technology, Vol. 155, No. 21, 19 November 2001, pp. 32-34

The FAA was poised to order inspections of the entire U.S. fleet of Airbus A300-600s as U.S. and French investigators late last week focused on wake turbulence and composite material structures as major factors in the Nov. 12 crash of American Airlines Flight 587. JFK's Automatic Terminal Information Service report at 8:15 a.m. indicated winds from 320 deg. at 11 kt. At 9:13 a.m. Japan Airlines Flight 47, a Boeing 747-400, began its takeoff roll. American Flight 587, N14053, followed, beginning its takeoff roll at 9:14:35 a.m., enroute to Santo Domingo, Dominican Republic, with the first officer at the controls. Preliminary radar readouts indicate Flight 587's flight path was offset to the east from that of JAL Flight 47 by about 0.7 naut. mi. and was behind it about 1.5 min. at the time of the last radar transponder return, as well as being about 800 ft. below. [To move 0.7 naut. mi. in 1.5 min. would have required a wind component of 28 kt. coming from the west.]

Fischbach, J. T.

"WAKE VORTEX VISUALIZER FOR AN AIRCRAFT"

US Patent 7,017,862 B1, March 2006.

A wake vortex visualizer for an aircraft having a self-contained device that is installed within the wing tip to emit a smoke-like trail from the wing tip automatically by the use of simple ball check valve connected between an orifice on the wing tip and a tank of vapor forming fluid during takeoff and landing of the aircraft such that other following aircraft may see and avoid the vortex generated by said aircraft during takeoff and landing.

Fischenberg, D.

"FLOW DETERMINATION METHOD"

US Patent Application 2011/0238330 A1, September 2011.

The invention relates to a method for determining a flow, wherein flow velocities in measuring direction are measured by means of sensors using at least one measuring position, comprising the following steps: a) Initializing parameters of a flow model representing the flow, b) Calculating simulated flow velocities in the measuring direction at least one measuring position according to the flow model representing the flow, c) comparing the measured flow velocities to the simulated flow velocities and adjusting the parameters of the flow model that influences the flow by minimizing a quality function that depends on the comparison result, and d) Repeating of steps b) and c) and determining the flow in dependency of the approximated flow model.

Fischenberg, D.

"WAKE ENCOUNTER FLIGHT TESTS PERFORMED WITHIN THE S-WAKE PROJECT"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

Within the fifth European framework technology project S-WAKE, full-scale wake vortex encounter flight tests were performed. In two campaigns (August 2001, March 2002) more than 100 encounters were flown with the aircraft Do128 and Cessna Citation, while the leading aircraft Vfw-614 ATTAS visualized its wake using a smoke generator installed on the outer left wing. Under favorable conditions, the smoke trace was visible up to 3 nm. Both follower aircraft were fully instrumented with inertial sensors and flow probes to measure the flow field characteristics of the wake vortex as well as the aircraft response during each encounter. The flight test data are of excellent quality and were used successfully for flow field determination as well as encounter model validation. The flight test data of the follower aircraft were evaluated to determine the flow field characteristics during each individual encounter. The flight path was reconstructed in high quality with system identification and flight path reconstruction methods. Using the flow sensor measurements, two different analytical velocity distributions (Burnham-Hallock, Lamb-Oseen) were investigated to match the measured flow field characteristics determining the model parameters with parameter identification techniques. The model parameters (circulation strength, core radius, separation, and vortex location) could be determined trustworthy for each encounter. The method seems to be a promising alternative to vortex parameter measurements by lidar. Two types of encounter models were successfully validated with the encounter flight test data: the Strip Method (SM) and the Lifting Surface Method (LSM). The encounter models were added to the basic flight mechanic models of the encountering aircraft (Do128, Cessna Citation) providing incremental aerodynamic coefficients. Measured control surface deflections as well as the determined vortex characteristics were considered. Comparing the model outputs to the measured flight test data, model benefits as well as model deficiencies could be demonstrated, the quality of both methods were compared.

Fischenberg, D.

"A METHOD TO VALIDATE WAKE VORTEX ENCOUNTER MODELS FROM FLIGHT TEST DATA"

ICAS Paper 2010-6.9.1, Sept. 2010, Nice, France.

A method is presented for assessing the accuracy of aerodynamic wake encounter models (also named 'aerodynamic interaction models'). The method uses real world data from in-situ measurements to produce the best possible fit of a given model structure. This process requires: (a) suitable encounter flight test data, (b) a high precision flight path reconstruction, (c) suitable parameters of an analytical vortex model, and (d) a high quality basic aerodynamic model. The vortex model parameters are identified in an a-priori step from the same wake encounter flight test data used for the subsequent validation of the aerodynamic interaction model. The accuracy assessment is done by analyzing the errors between model outputs and the corresponding flight test data. The paper reflects the used incremental Strip Model structure and recommends appropriate a-priori data. Simulation results are analyzed, and strip model extensions are implemented which imply a notable model quality improvement.

Fish, S.

"VORTEX DYNAMICS IN THE PRESENCE OF FREE SURFACE WAVES"

Physics of Fluids, Vol. A3, No. 4, April 1989, pp. 504-506.

Results are presented of flow visualization experiments on vortex pairs launched toward a free surface containing waves. The two-dimensional vortex pair is generated with an initial depth/separation value of 1.0 using a pivoting pair of flaps. Two-dimensional waves are generated with an oscillating-plate-type wavemaker. The resulting flows indicate a strong interaction between the waves and the vortex trajectories. The aspects of vortex/wave interactions examined are (1) elimination of the 'rebounding' effect on the upstream traveling vortex and (2) an increase in rebound effect on the downstream vortex. These influences of the surface waves on the vortex appear to be related to the near-surface drift current produced by the waves.

Fitzsimons, B.

"PLANNING FOR THE 600-SEATER"

Airport Forum, Vol. 23, No. 6, December 1993, pp.13-14

Airports and airlines need to do some hard thinking about large transports. From wake vortex effect to fire-fighting, there are new dimensions to consider.

Flaszyrski, P., Szantyr, J. A. and Tesch, K.

"NUMERICAL PREDICTION OF STEADY AND UNSTEADY TIP VORTEX CAVITATION ON HYDROFOILS"

Polish Maritime Research, Vol. 19, No. 3, 2012, pp. 3-15.

The article presents the numerical method for prediction of tip vortex cavitation generated on hydrofoils. This method has been developed in the course of numerical and experimental research described in earlier publications. The objective of the research was to design the optimum discrete grid

structure for this specific computational task and to select the best turbulence model for such an application. The article includes a short description of the method and a computational example demonstrating its performance. In this example the results of numerical prediction of the cavitating tip vortex obtained from two commercial CFD codes are compared with experimental photographs taken in the cavitation tunnel in the corresponding flow conditions. Altogether nine different flow conditions are tested and analyzed, but only selected results are included. The accuracy of the numerical predictions is discussed and the reasons for minor existing discrepancies are identified. The unsteady tip vortex calculations are also presented, showing the fluctuations of the transverse velocity components predicted for three cross-sections of the cavitating vortex kernel.

Flax, A. H.

"COMMENT ON 'SIMPLIFIED METHODS OF PREDICTING AIRCRAFT ROLLING MOMENTS DUE TO VORTEX ENCOUNTERS'"

J. Aircraft, Vol. 14, No. 11, November 1977, pp. 1151-1152

The simple formula derived by Barrows relating the aerodynamic rolling moment according to strip theory to the rolling moment according to lifting-line theory for a wing of elliptical planform subjected to an arbitrary antisymmetric angle-of-attack distribution is a long-established and well-known result in wing theory. Extensive applications of this formula to stability and control and to aeroelasticity have been given in the literature. There is a similar formula for the lift on an elliptic wing due to an arbitrary symmetric angle-of-attack distribution. These special results for the elliptic wing follow from the fact that for this planform all the coefficients of the Fourier series for spanwise circulation distribution in lifting-line theory may be determined explicitly and exactly by quadrature without solving simultaneous equations (which in principle are infinite in number). As is well known in lifting-line theory, for all planforms the total lift depends only on the first Fourier coefficient, whereas the total rolling moment depends only on the second coefficient.

Flechner, S. G., Jacobs, P. F. and Whitcomb, R. T.

"A HIGH SUBSONIC SPEED WIND-TUNNEL INVESTIGATION OF WINGLETS ON A REPRESENTATIVE SECOND-GENERATION JET TRANSPORT WING"

NASA TN D-8264, July 1976, NASA Langley Research Center, Hampton, VA.

This paper discusses the effects of winglets (described in NASA TN D-8260) on the aerodynamic forces and moments, loads, and crossflow velocities behind the wing tip. The results of the investigation indicate that winglets significantly reduce the drag coefficient at lifting conditions. The experiments were conducted in the Langley 8-foot transonic pressure tunnel at Mach numbers from 0.70 to 0.83 and over a lift coefficient range up to 0.65. A semispan model was used.

Fleig, O. and Arakawa, C.

"LARGE-EDDY SIMULATION OF TIP VORTEX FLOW AT HIGH REYNOLDS NUMBER"

AIAA Paper No. 2004-0261, Reno, NV, January 2004

Simulations using up to 300 million grid points are performed on the Earth Simulator in Japan, the fastest supercomputer in the world. The present work is the first attempt to simulate a finite blade with a tip in an incident flow and its associated tip vortex and acoustic field at a Reynolds number in the order of a million using direct compressible LES (Large-Eddy Simulation). For validation purposes, the flows around a NACA0012 blade section as well as finite blade at lower Reynolds number are simulated. It is a wall resolved simulation using the Smagorinsky eddy viscosity model. Angles of attack between 5 and 11 degrees are studied at Reynolds numbers ranging from $4.06 \times 100,000$ to $2.87 \times 1,000,000$. The simulation results showed that the tip vortex plays a major role in aerodynamic noise generation. The present large-scale simulation can provide information about the physical phenomena causing tip vortex flow and tip noise at high Reynolds numbers. This information can be used in various engineering applications such as aerospace and wind energy and could help to design blade tips for reduced noise emission.

Fleischmann, D. and Lone, M.

"ANALYSIS OF WAKE SURFING BENEFITS USING A FAST UNSTEADY VORTEX LATTICE METHOD"

AIAA Paper 2019-0264, January 2019, San Diego, CA.

The computer simulation framework Flexit is used to analyze the fuel economy benefit of aircraft wake surfing. Wake surfing involves multiple aircraft flying in close formation during cruise conditions to reduce overall induced drag and improve overall fuel efficiency. The aircraft fly in echelon such that the kinetic energy lost in vortices generated by the lead aircraft can be partially recovered by the following aircraft flying in regions of the wake where induced velocities have an upwardly directed vertical component. We build on recent theoretical and flight test work by developing a medium fidelity methodology using Flexit for predicting potential performance benefits of wake surfing. We present results from a specific systematic parametric study that corresponds to a series of recent flight tests with two C-17 transport aircraft to demonstrate the methodology and predict the fuel savings that can be obtained by different arrangements of aircraft in a wake surfing formation. The predictions are compared with the flight test data and the trends observed in our simulations agree with the trends of the full-scale tests.

Fleming, P., Annoni, J., Churchfield, M., Martinez-Tossas, L. A., Gruchalla, K., Lawson, M. and Moriarty, P.

"A SIMULATION STUDY DEMONSTRATING THE IMPORTANCE OF LARGE-SCALE TRAILING VORTICES IN WAKE STEERING"

Wind Energy Science, Vol. 3, 2018, pp. 243-255.

In this paper, we investigate the role of flow structures generated in wind farm control through yaw misalignment. A pair of counter-rotating vortices is shown to be important in deforming the shape of

the wake and in explaining the asymmetry of wake steering in oppositely signed yaw angles. We also demonstrate that vortices generated by an upstream turbine that is performing wake steering can deflect wakes of downstream turbines, even if they are themselves aligned. We encourage the development of improvements to control-oriented engineering models of wind farm control, to include the effects of these large-scale flow structures. Such a new model would improve the predictability of control-oriented models. Further, we demonstrate that the vortex structures created in wake steering can lead to greater impact on power generation than currently modeled in control-oriented models. We propose that wind farm controllers can be made more effective if designed to take advantage of these effects.

Fletcher, T. M. and Brown, R. E.

"HELICOPTER TAIL ROTOR THRUST AND MAIN ROTOR WAKE COUPLING IN CROSSWIND FLIGHT"

Journal of Aircraft, Vol. 47, No. 6, November-December 2010, pp. 2136-2148.

The tail rotor of a helicopter with a single main rotor configuration can experience a significant reduction in thrust when the aircraft operates in crosswind flight. Brown's vorticity transport model has been used to simulate a main rotor and tail rotor system translating at a sideslip angle that causes the tail rotor to interact with the main rotor tip vortices as they propagate downstream at the lateral extremities of the wake. The tail rotor is shown to exhibit a distinct directionally dependent mode during which tail rotors that are configured so that the blades travel forward at the top of the disk develop less thrust than tail rotors with the reverse sense of rotation. The range of flight speeds over which this mode exists is shown to vary considerably with the vertical location of the tail rotor. At low flight speeds, the directionally dependent mode occurs because the tail rotor is immersed within not only the downwash from the main rotor but also the rotational flow associated with clusters of largely disorganized vorticity within the main rotor wake. At higher flight speeds, however, the tail rotor is immersed within a coherent super-vortex that strongly influences the velocity field surrounding the tail rotor.

Flight Safety Technologies (FST), and Lockheed Martin

"SOCRATES WAKE VORTEX DETECTION AND TRACKING: A TECHNICAL STATUS REPORT"

Report DTRS57-03-D-30024, November 2004, Volpe National Transportation Systems Center, Cambridge, MA

SOCRATES is a laser based passive opto-acoustic wake turbulence detection concept being developed by Flight Safety Technologies, Inc. and Lockheed Martin Corporation. The claim of the SOCRATES development team is that it can detect and track wake vortices by passively sensing the sound that emanates from aircraft wakes. In 2003, a fundamental wake acoustic testing to better understand the wake acoustic phenomenology was conducted at the Denver International Airport using a NASA-Volpe fielded phased microphone array. This fundamental test also provided an opportunity to better understand the status of the SOCRATES development up to that point in time. The purpose of this

report is to, from the developer's perspective, describe the status of the SOCRATES development effort. The system is described, along with other background information, in sections 2 and 3. The nature of the sound generated by aircraft wake vortices is discussed in section 4, and comparison between SOCRATES and LIDAR-derived wake tracks is presented in section 5. Remaining challenges and conclusions are presented in sections 6 and 7.

Flores-Garcia, D., Fernandez-Roque, T. and Hernandez-Tamayo, J.

"VORTEX IN THE WAKES OF AIRPLANES"

Fluid Dynamics in Physics, Engineering and Environmental Applications, J. Klapp et al. (editors), Environmental Science and Engineering, 2013, Springer-Verlag Berlin Heidelberg, pp. 345-351.

This paper describes the disturbances caused by wing trailing vortices and their effect on aircraft flying into them. We briefly discuss the physical characteristics of the wing trailing vortices together with their control and alleviation and emphasis is done about the importance that it has in order to diminish the problems generated by the increase in air traffic and in the flight safety.

Fogg, J. G.

"VORTEX PAIR INSTABILITIES IN GROUND EFFECT"

MS Thesis, May 2001, Cornell University, Ithaca, NY.

In this thesis we investigate the development of the long-wavelength instability of a counter-rotating vortex pair in the presence of the ground. Our experiments involve detailed visualizations and velocimetry of the vortex pair, which is generated underwater by two rotating plates. We first investigate the dynamics of the instability far from the ground. We find that the instability amplitude grows exponentially to the point of reconnection, at which point the vortex pair transitions to a series of vortex rings. In the presence of the ground, we find that the reconnection and subsequent break-up of the vortex pair into a series of vortex rings can be inhibited. We find that there exists a critical initial height for the vortex pair, above which the vortices reconnect and form rings. Below this critical height, the vortices separate due to ground effects, even if partial reconnection has taken place. We also discover that the instability plane rotates as the vortex pair interacts with the ground, in a direction contrary to that one might expect, based on image vorticity considerations. We present experimental measurements using DPIV of the vortex-ground interaction, including the well-known rebound effect as well as measurement of the generation of secondary vorticity.

Follin, G. J.

"THE TURBULENCE STRUCTURE OF TRAILING VORTEX WAKES"

MS Thesis, 1996, Virginia Polytechnic Institute and State University, Blacksburg, VA.

The present investigation is a two-part study of the mean flow and turbulence structure of isolated vortices and counter-rotating vortex pairs. In the first part, the turbulence structure of an isolated vortex was studied using three-component velocity measurements. Vortices were generated using two symmetrical airfoils. Measurements were made in cross-sectional grids and profiles over a range of Reynolds numbers and downstream distances. Contours of axial normal stress were high-pass filtered to remove the contributions of wandering to the velocity fluctuations. This process reveals a vortex core which is laminar and is surrounded by a region of high turbulence. Core velocity profiles reveal that maximum tangential velocity increases with Reynolds number and decreases with distance downstream. Core radius increases with distance downstream and decreases with Reynolds number. In the second part, flow visualizations of the wake behind a delta wing model were made for a range of Reynolds numbers and lift coefficients. These visualizations reveal the near-instantaneous turbulence structure of the wing wake which is dominated by a vortex pair and a connecting 'braid' wake. The braid spacing decreases with increasing Reynolds number and is independent of lift coefficient. The extent of the braid downstream of the wing increases with lift coefficient and decreases with increasing Reynolds number. The large turbulent scales in the wing wake were found to increase in discrete jumps indicating some sort of reorganization of turbulence such as pairing. This reorganization of turbulence was found to occur more quickly as Reynolds number is increased.

Follin, G. J. and Devenport, W. J.

"EFFECTS ON THE TURBULENT STRUCTURE OF A COUNTER-ROTATING VORTEX PAIR"

AIAA Paper No. 1996-1959, New Orleans, June 1996

Flow visualizations of the wake of a 75deg delta wing were made by laser illumination of fluorescein dye over a range of Reynolds numbers and lift coefficients. These visualizations reveal the wing wake to be made up of a counter-rotating vortex pair connected by a spanwise periodic structure called the 'braid' wake. The wavelengths of the dominant structures in the wing wake were found to increase with distance behind the wing in discrete jumps, implying some sort of reorganization of turbulence from small to large scales. Increasing Reynolds number was found to decrease the braid spacing and the extent of the braid wake behind the wing. The redistribution of turbulence from small to large scales was found to speed up with increasing Reynolds number. Increasing lift coefficient was found to increase the extent of the braid. The vertical extent of the wake also appeared to increase with the lift coefficient.

Follin, G. J. and Devenport, W. J.

"THE TURBULENCE STRUCTURE OF TRAILING VORTEX WAKES"

Report VPI-AOE-235, 1996, Virginia Polytechnic Institute and State University, Blacksburg, VA.

The present investigation is a two-part study of the mean flow and turbulence structure of isolated vortices and counter-rotating vortex pairs. In the first part, the turbulence structure of an isolated vortex was studied using three-component velocity measurements. Vortices were generated using two

symmetrical airfoils. Measurements were made in cross-sectional grids and profiles over a range of Reynolds numbers and downstream distances. Contours of axial normal stress were high-pass filtered to remove the contributions of wandering to the velocity fluctuations. This process reveals a vortex core which is laminar and is surrounded by a region of high turbulence. Core velocity profiles reveal that maximum tangential velocity increases with Reynolds number and decreases with distance downstream. Core radius increases with distance downstream and decreases with Reynolds number. In the second part, flow visualizations of the wake behind a delta wing model were made for a range of Reynolds numbers and lift coefficients. These visualizations reveal the near-instantaneous turbulence structure of the wing wake which is dominated by a vortex pair and a connecting 'braid' wake. The braid spacing decreases with increasing Reynolds number and is independent of lift coefficient. The extent of the braid downstream of the wing increases with lift coefficient and decreases with increasing Reynolds number. The large turbulent scales in the wing wake were found to increase in discrete jumps indicating some sort of reorganization of turbulence such as pairing. This reorganization of turbulence was found to occur more quickly as Reynolds number is increased.

Fonesca, G. F., Bodstein, G., C. R. and Hirata, M. H.

"NUMERICAL SIMULATION OF INVISCID INCOMPRESSIBLE TWO-DIMENSIONAL AIRFOIL-VORTEX INTERACTION IN GROUND EFFECT"

Journal of Aircraft, Vol. 40, No. 4, July-August 2003, pp. 653-661

A numerical inviscid vortex method is employed to study the unsteady, two-dimensional, incompressible flow that occurs during an airfoil-vortex interaction in the vicinity of a ground plane. The airfoil bound vorticity is modeled using a panel method with linear piecewise-continuous vorticity distribution. The vortex is considered to be a point vortex, and the ground effect is obtained using the method of images. Point vortices are also generated at the airfoil trailing edge to ensure that circulation is conserved and that the Kutta condition is satisfied. All vortices are convected using a first-order Lagrangian time-marching scheme. After code validation, numerical results for the airfoil-vortex interaction in ground effect reveal that the loading on the airfoil is affected by the thickness, angle of attack, and height of the airfoil above the ground, as well as the vortex strength, direction of rotation, and distance to the airfoil. The wake evolution is nonlinear and strongly influenced by the interaction, whereas the pressure distribution on the ground presents steep adverse gradients.

Fonseca, G. F., Bodstein, C. R. and Hirata, M. H.

"NUMERICAL SIMULATION OF INVISCID INCOMPRESSIBLE TWO-DIMENSIONAL AIRFOIL-VORTEX INTERACTION IN GROUND EFFECT"

Journal of Aircraft, Vol. 40, No. 4, July-August 2003, pp. 653-661.

A numerical inviscid vortex method is employed to study the unsteady, two-dimensional, incompressible flow that occurs during an airfoil-vortex interaction in the vicinity of a ground plane. The airfoil bound vorticity is modeled using a panel method with linear piecewise-continuous vorticity

distribution. The vortex is considered to be a point vortex, and the ground effect is obtained using the method of images. Point vortices are also generated at the airfoil trailing edge to ensure that circulation is conserved and that the Kutta condition is satisfied. All vortices are convected using a first-order Lagrangian time-marching scheme. After code validation, numerical results for the airfoil-vortex interaction in ground effect reveal that the loading on the airfoil is affected by the thickness, angle of attack, and height of the airfoil above the ground, as well as the vortex strength, direction of rotation, and distance to the airfoil. The wake evolution is nonlinear and strongly influenced by the interaction, whereas the pressure distribution on the ground presents steep adverse gradients.

Fontane, J., Brancher, P., Antkowiak, A. and Febre, D.

"NONMODAL STABILITY ANALYSIS OF THE LAMB-OSEEN VORTEX"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

The present contribution aims to report the investigation of the vortex meandering phenomenon. Isolated columnar vortices are known to be asymptotically stable but often present behaviors not well understood. Among them, the vortex meandering consists in an erratic displacement of the vortex core acknowledged to considerably embarrass experimentalists. These phenomena of energy growth are related to the non-normality of the corresponding dynamical operator and need to be studied within the frame of the nonmodal stability analysis. We look first at the optimal perturbations, i.e. the initial conditions maximizing their energy growth for any given time. From the evolution of these disturbances, two mechanisms of energy growth are identified. The first one, called the anti-lift-up, leads to the generation of vortex rings in the potential region around the vortex. The second one is a resonance phenomenon leading to the emergence of a wave in the vortex core through a mechanism combining Orr and induction effects. The emergence of the displacement wave is thus a good candidate for the vortex meandering phenomenon. Secondly, the robustness of these perturbations is considered in a more realistic case. The vortex is continuously forced by a random white noise, aimed to be representative of any generic disturbance occurring in real flows. With this stochastic approach, optimal disturbances are generally observed to emerge, except in cases when there may exist strong sub-optimal perturbations that compete well with optimal ones.

Fonti, E.

"MEASUREMENTS OF AIRCRAFT WAKE VORTICES IN GROUND PROXIMITY WITHIN AN ATMOSPHERIC BOUNDARY LAYER WIND TUNNEL"

MS Thesis, 2010, Cranfield University, Cranfield, UK.

The vortex wake characteristics of aircraft during landing and take-off are of interest in connection with both the safety of following aircraft penetrating the vortex and the dispersion of engine exhaust plumes. A series of measurements were carried out in an Atmospheric Boundary Layer Wind Tunnel (ABLWT) to identify and characterize both the mean and turbulent flow field of a pair of wake vortices

in ground proximity. The ABLWT simulation at 1:200th scale utilized a flat plate delta planform wing to produce a wake vortex system with an initial vortex core separation consistent with that expected for the DLR VFW614 ATTAS aircraft during the final stages of the approach and flare prior to landing to aid possible future full- scale validation. Evaluation of the mean flow field was obtained in vertical planes downstream of the model 0.18b to 7.48b (b is the wing span) using a traversing 5-hole pressure probe. Vortex trajectory, circulation decay, vorticity decay and core radius evolution were tracked at wing heights of 0.93b to 2.24b within the wind tunnel working section, showing the ground proximity effect on the vortex system. The vortices were seen to sink behind the wing and diverge moving downstream, as expected. The rate of descent was shown to decrease as the wing approaches the ground. The circulation was fitted to a straight line with enough accuracy for all the wing heights investigated. An inviscid model for the prediction of the trajectory of a vortex pair was developed. It uses an infinite vortex sheet to simulate the interaction between the vortices and the ground when these are in the ground effect region. The experimental results were compared to the model showing good agreement. Measurements of the instantaneous flow field were acquired by means of a Stereo Particle Velocimetry system and were used to investigate the effect of turbulence on the vortex system. The mean field was compared to the fluctuating field showing the random and intermittent nature of the turbulence. Turbulence intensity, Reynolds stresses, spatial velocity correlations and correlation lengths were calculated and discussed. However, further work is needed to acquire a more comprehensive set of PIV data in the ABLWT to draw stronger conclusions.

Ford, R. and Smith, S. G. L.

"SCATTERING OF ACOUSTIC WAVES BY A VORTEX"

J. Fluid Mech., Vol. 386, 1999, pp. 305-328

We investigate the scattering of a plane acoustic wave by an axisymmetric vortex in two dimensions. We consider vortices with localized vorticity, arbitrary circulation, and small Mach number. The wavelength of the acoustic waves is assumed to be much longer than the scale of the vortex. This enables us to define two asymptotic regions: an inner, vortical region, and an outer, wave region. The solution is then developed in the two regions using matched asymptotic expansions, with the Mach number as the expansion parameter. The leading-order scattered wave field consists of two components. One component arises from the interaction in the vortical region, and takes the form of a dipolar wave. The other component arises from the interaction in the wave region.

Fox, S. M.

"C-17 AIRDROP SIMULATION"

MS Thesis, Air Force Institute of Technology, WPAFB, OH, March 1998

We develop an object-oriented simulation that models the airdrop mission of the newest U.S. transport aircraft, the C-17 Globemaster III. The simulation, written in MODSIM III is based on three basic object types: a C-17, a wake vortex, and a paratrooper. The aircraft object provides the required

aerodynamic constants for simulating the wake vortices generated off each wing tip; the vortex object includes velocity field and decay models as well as a position algorithm; and, the paratrooper object implements a 6-degree of freedom trajectory model. After considering two validation scenarios, we generate vortex encounter information for various formations and wind conditions, and quantify the associated risk of paratrooper/vortex encounters in a potential encounter rate. Time over the DZ is a primary concern in any airdrop operation, and the results of this analysis form a tool that allows the ground commander to assess the risk involved in decreasing that time. We also present a 3D visualization of the simulation output that may be used for mission planning and prototyping of new aircraft formations or tactics.

Fox, S. M., Bailey, T. G. and Carlton, W. B.

"PERSONNEL AIRDROP SIMULATION"

Simulation, Vol. 76, No. 1, Jan. 2001, pp. 4-21

We develop an object-oriented simulation that models the airdrop mission of a US transport aircraft, the C-17 Globemaster III. The simulation, written in MODSIM III, is based on three basic object types: an aircraft, a wake vortex, and a paratrooper. The aircraft object provides the required aerodynamic constants for simulating the wake vortices generated off each wingtip; the vortex object includes velocity field and decay models as well as a position algorithm; and the paratrooper object implements a 6-degree-of-freedom trajectory model. Using the simulation, we generate vortex encounter information for various formations and wind conditions, and quantify the associated risk of paratrooper/vortex encounters in a potential encounter rate. Time over the drop zone is a primary concern in any airdrop operation, and the results of this analysis form a tool that allows the ground commander to assess the risk involved in decreasing that time.

Frakes, J. F.

"WING TIP VORTICES SUPPRESSOR"

US Patent 4,478,380, October 1984.

A wing tip vortices suppressor utilizing a scoop having an inlet at the lower, leading surface of the wing and an outlet at the upper, trailing surface to reduce turbulence causing pressure differential across the wing. A turbulence fence is used at the tip to account for the frictional losses of the air flowing through the scoop and other phenomena that prevent exact pressure equalization.

Francis, D. G.

"DEVELOPMENT OF A VORTEX LASER DOPPLER VELOCIMETER"

Proceedings of the National Aerospace Electronics Conf., IEEE, 1971, pp. 36-40

The paper describes basic laser Doppler velocimeter theory and outlines the vortex laser Doppler velocimeter program at the Arnold Engineering Development Center. The object of the program is to design, develop, and place into operation a three-component laser Doppler velocimeter system capable of mapping velocity profiles of aircraft wake turbulence at altitudes up to 1000 feet.

Francis, M. S.

"AN EXPERIMENTAL INVESTIGATION OF WING TRAILING VORTEX FORMATION"

FJSRL TR-76-0013, August 1976, US Air Force Academy, Colorado Springs, CO.

The incompressible flow field in the vicinity of a lifting rectangular finite wing is investigated experimentally to ascertain the nature and detailed characteristics of the formation and early development of a trailing vortex. The apparatus was designed and fabricated to facilitate a direct comparison of real flow data with existing theories and flow models. The inboard potential flow region was observed to exhibit the simplifying characteristic of a spanwise cross-flow velocity component which is independent of the surface normal coordinate. As a result, a possible ambiguity in the determination of the stream-wise vorticity component was removed. Graphs of the near-surface (bound) vorticity distribution are presented along with a map of Prandtl bound vortex filaments. The associated bound circulation function could be expressed approximately as the product of two separable functions of the planform spatial coordinates. Measurements at the wing trailing edge are employed to show that the properly non-dimensionalized characteristic vorticity distribution in this region is independent of angle of attack.

Francis, M. S. and Kennedy, D. A.

"FORMATION OF A TRAILING VORTEX"

Journal of Aircraft, Vol. 16, No. 3, March 1979, pp. 148-154

The incompressible flow field in the vicinity of a lifting rectangular finite wing is investigated experimentally to ascertain the nature and detailed characteristics of the formation of a trailing vortex. The mean velocity field was mapped directly using a linearized constant temperature hot-wire anemometry probe in conjunction with a precision wind-tunnel traversing mechanism. The associated vorticity field was inferred from these measurements through a spatial contour integration procedure. The existence of several identifiable flow regions exhibiting similar characteristics was established and verified with both hot-wire and flow visualization data. The nature of the near surface bound vorticity distribution is described including a map of the Prandtl-bound vortex filaments. Measurements at the wing trailing edge show that the properly nondimensionalized characteristic vorticity distribution in this region is independent of angle of attack. Shed vorticity emanating from the lower aerodynamic surface near the wing tip was observed to roll up adjacent to the tip and roll over onto the upper wing surface at a chordwise location which depends on the wing orientation. The presence and behavior of this structure which possesses an identifiable core is suggested as the cause of the modified pressure distribution (lift increment) normally observed in this region.

Francis, T. B. and Katz, J.

"OBSERVATIONS ON THE DEVELOPMENT OF A TIP VORTEX ON A RECTANGULAR HYDROFOIL"

Journal of Fluids Engineering, Vol. 110, June 1988, pp. 208-215.

The present paper describes a flow visualization study that focuses the development of a tip vortex on a rectangular NACA-66 hydrofoil. The experiments have been performed in a towing tank. Illumination with a thin laser sheet together with distribution of dye have been utilized as a means of observation. The results demonstrate the growth of the vortex along the chord, the increase in its dimensions with increasing incidence angle and decreasing Reynolds number. They also show that the center of the vortex moves inward towards the root with increasing incidence angle, increasing chordwise location, and decreasing velocity. Empirical relations for these trends have been computed. The observations also demonstrate that the flow around the tip is dominated by multiple vortex structures that include the primary vortex, a counter rotating structure, shear layer eddies, and several other secondary vortices.

Franke, J. M.

"ANALYSIS OF THE DYNAMICS OF WAKE VORTICES IN THE ATMOSPHERIC BOUNDARY LAYER"

ISBN-3-923624-27-1, 1995, University of Hannover, Hannover, Germany

The longevity and high intensity of wakes of landing aircraft may create hazards to subsequent air traffic. This study compares the results of extensive field experiments with results of numerical simulations and uses them to develop a wake displacement model. It was confirmed that vortex life is greatly determined by the wind conditions prevailing in the vortex propagation area. The increasing turbulent kinetic energy in higher main flows leads to premature disintegration phenomena of the wake. While the mean life of all measured wakes is only 78 s, lives of more than 2 minutes can be reached at lower horizontal wind speeds. The longest measured life of a wake is 192 s. It is shown that vortex life is also influenced by atmospheric stability. Under stable layering conditions a longer vortex life must be expected. The measure of this influence is more marked in the measurements than that apparent in numerical simulations. [In German.]

Frauenkron, H., Biegholdt, J., Maiss, M., Nalpanis, P. and Smith, E.

"A STATISTICAL EVALUATION OF NAVIGATIONAL PERFORMANCE OF ILS-APPROACHES AT FRANKFURT INTERNATIONAL AIRPORT"

FLIP Version 2.0, DFS Deutsche Flugsicherung GmbH, February 2001, Offenbach, Germany

This study involved extensive data collection, processing, and analysis for radar tracks of aircraft approaching Frankfurt International Airport. Data obtained over a limited period of three days using the high precision Skyguard radar system were used to validate 4 months of Airport Surveillance Radar

data. The data indicate that the deviations from the ILS localizer and glide slope are well within the tolerances set by ICAO (typically within 0.07 degrees, four times better than ICAO specifies for lateral deviations: typically 0.03 to 0.05 degrees (0.20-0.35 dots), for height deviations). The height deviations agree with statements of pilots that they avoid wake vortices by flying slightly above the glide slope.

Frazier, J. W. and Gopalarathnam, A.

"OPTIMUM DOWNWASH BEHIND WINGS IN FORMATION FLIGHT"

Journal of Aircraft, Vol. 40, No. 4, July 2003, pp. 799-803

The calculus-of-variations approach previously used by Jones for determining minimum induced drag of single wings has been extended to handle multiple wings in formation flight with constraints on the lift and rolling moment for each wing. The approach shows that the lift distributions for wings in formation flight with constraints on the lift and rolling moments on each wing must result in a linear variation in the Trefftz-plane downwash for the total induced drag of the formation to be a minimum. Like the constrained-minimization approach, the current formulation is also valid only for formation geometries in which the wake traces of the wings in the Trefftz plane do not intersect or overlap with each other. Although there does not appear to be any significant computational advantage to the present method when compared to that of a constrained-minimization technique, the present method provides a simple closed-form expression for the optimum downwash and, thus, provides additional insight into the aerodynamics of ideal formation flight.

Frech, M.

"A SIMPLE METHOD TO ESTIMATE THE EDDY DISSIPATION RATE FROM SODAR/RASS MEASUREMENTS"

16th Symposium on Boundary Layers and Turbulence, AMS, 2004, Portland, Oregon.

The dissipation rates obtained from SODAR/RASS for the stable/neutral cases using a scaled TKE show an acceptable agreement with eddy dissipation rates obtained from LIDAR measurements. For unstable situation, a stability correction needs to be developed which is work currently under way.

Frech, M.

"ESTIMATING THE TURBULENT ENERGY DISSIPATION RATE IN AN AIRPORT ENVIRONMENT"

Boundary-Layer Meteorol, Vol. 123, 2007, pp. 385-393

This note reports on the influence of aircraft wake vortices on the estimation of the turbulent energy dissipation rate using sonic anemometer measurements near the runway threshold. The wake vortex traces, which are generated at a height of about 65 m and subsequently evolve in ground effect, are clearly visible in the velocity components and temperature. The observed temperature increase of 1 K appears related to the stably stratified atmospheric surface layer. The dissipation rate is estimated from the longitudinal velocity power spectrum for a sample in a nocturnal boundary layer with and

without a wake vortex signal. In both cases an inertial subrange is found. For the analyzed sample the estimated dissipation rate is a factor of ten larger compared to the undisturbed sample. Implications for operational wake avoidance systems are discussed.

Frech, M. and Holzaepfel, F.

"SKILL OF AN AIRCRAFT WAKE VORTEX TRANSPORT AND DECAY MODEL USING WEATHER PREDICTION AND OBSERVATION"

Proceedings of the Twelfth Conference on Aviation Range and Aerospace Meteorology, American Meteorological Society, Atlanta, Georgia, Feb. 2006

To safely reduce aircraft separation during approach and landing, the wake vortex behavior along the glide path must be known and predicted. This requires in principle the knowledge of wake vortex relevant meteorological parameters along the entire glide path where typically continuous meteorological measurements of all relevant variables are not feasible. For multiple purposes a one-year meteorological data base for the Frankfurt Terminal area has been generated using NOWVIV. The skill of the nowcasting system NOWVIV (Nowcasting Wake Vortex Impact Variables, Gerz et al. 2005) to predict these environmental parameters is assessed. This one-year data set comprises typical weather conditions and includes already typical features of a long-term surface wind climatology. It enables to test new operational concepts with realistic meteorological input and to estimate the potential for aircraft separation reduction. It may also be used within risk assessments for prototype wake-vortex advisory systems (Gerz et al. 2005). A subset of the one-year data base is analyzed in detail for a period of 40 days where a dedicated wake measurement campaign was carried out at Frankfurt airport in fall 2004 (Frech et al., 2005). In total 231 wake vortex pairs generated by heavy aircraft in ground proximity were tracked and characterized by LIDAR. During this measurement campaign a SODAR/RASS and a LIDAR provided profile measurements of meteorological variables. These data are used to analyze the quality of the predicted profiles of wind, temperature, and turbulence (Frech et al., 2005). Furthermore, we carry out a skill analysis to investigate the potential of NOWVIV as a real-time prediction system where we focus on the ability to predict pre-defined cross wind thresholds. The skill of NOWVIV is compared to the skill of a simple cross wind persistence model based on SODAR measurements. For this purpose, we assume that a given measured cross wind profile is valid over the whole forecast lead time and evaluate the skill of the forecast with increasing lead time every 10 minutes.

Frech, M. and Holzaepfel, F.

"SENSITIVITY OF A WAKE VORTEX MODEL TO METEOROLOGICAL INPUT VARIABLES"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

A large eddy simulation (LES) of the decay of wake vortices in the convective boundary (CBL) is used to investigate the predictive capabilities of a simple wake vortex transport and decay model (VORTEX) based on Corjon and Poinot (1996). The sensitivity of VORTEX forecasts on the quality of

meteorological input parameters is studied, since only limited meteorological background information is available operationally. We test three simple methods to account for the structure of the CBL. Area-averaged CBL profiles computed from LES and simple model assumptions on the structure of the CBL using surface data are used as input. A simple third approach uses meteorological LES data at $z=16$ m which is a height representative for tower measurements. For the trajectories, the first and second approach yields similar results. The predicted residence corridors are erroneous for some time steps. The errors are quantified. The third approach yields conservative results, which is an important result from an operational point of view. For the CBL case, this study shows that surface measurements would be sufficient to predict WV trajectories along the glide path with acceptable accuracy. We also test recently published parameterizations of the turbulent decay of wake vortices. We find a weak sensitivity of the predicted corridor on the type of parameterization. The precise knowledge of the meteorological background conditions is more important.

Frech, M. and Holzaepfel, F.

"A PROBABILISTIC PREDICTION SCHEME FOR WAKE VORTEX EVOLUTION IN A CONVECTIVE BOUNDARY LAYER"

Air Traffic Control Quarterly, Vol. 10, No. 1, 2002, pp. 23-41

The convective boundary layer's relationship to the formation and dissipation of wake vortices is studied in this research, which used large eddy simulation (LES) data in a parametric model. Profiles of the turbulent kinetic energy and variances created with LES data for an evolving convective boundary layer match profiles of a stationary convective boundary layer. The LES data is also used to verify wake vortex predictions by models, which have only limited meteorological data about elements such as cross winds which can dissipate wake vortices. Models and LES data tend to predict conservative rates of vertical dissipation for wake vortices until the rapid phase of decay starts. Then decay is underestimated, which produces conservative recommendations for separations of aircraft. The authors conclude that turbulent kinetic energy predictions are sufficient for predicting wake vortices. More work is needed to develop methods to predict short-term pictures of boundary layers every 30 minutes. Also needed is work on learning about meteorological conditions that contribute to wake vortices, particularly wind shear, with the goal of predicting wake vortices for an entire glide path.

Frech, M. and Holzaepfel, F.

"SKILL OF AN AIRCRAFT WAKE-VORTEX MODEL USING WEATHER PREDICTION AND OBSERVATION"

J. Aircraft, Vol. 45, No. 2, March-April 2008, pp. 461-470

The performance of the two-phase probabilistic wake-vortex transport and decay model using numerical weather prediction and weather observations as input is analyzed using data from a wake measurement campaign carried out at Frankfurt airport during fall 2004. The wake-vortex observations include wakes evolving in and out of ground effects. The best forecast quality is achieved for wakes evolving in ground effect. We include the simplified hazard-area prediction model to compute the time

to clear the corridor from hazardous wakes and to assess the potential capacity gain for single-runway operations. The highest-capacity potential can be expected when weather observations are employed for wake predictions. The limiting factor for capacity is wakes evolving in ground effect. Out of ground effect, the self-induced vertical transport of the wake vortex proves to be a robust mechanism to clear the approach corridor in an efficient way. This is found independently from the source of meteorological input. In contrast, the consideration of lateral wake transport alone leads to marginal-capacity potential. The analysis also shows that weather data along the glide path can be provided by numerical weather prediction for safe wake prediction.

Frech, M. and Zinner, T.

"CONCEPT OF WAKE VORTEX BEHAVIOR CLASSES"

Journal of Aircraft, Vol. 41, No. 3, May-June 2004, pp. 564-570

The concept of wake vortex behavior classes is introduced. Rather than consider the individual wake vortex evolution, diagnosis of the meteorological situation causing a characteristic wake vortex behavior is proposed. We define four wake vortex behavior classes that explicitly refer to both the wake vortex transport and the decay behavior. The statistical analysis of the Memphis wake vortex database supports this new concept and also shows the distinct influence of weather on wake vortex behavior. The analysis indicates that the high-level safety of International Civil Aviation Organization (ICAO) separations between consecutive aircraft is primarily due to the transport of wake vortices out of a flight corridor. It is found that, depending on atmospheric conditions, a significant fraction of wake vortices does not decay enough to satisfy the existing ICAO separations. Of these wake vortices, a small fraction is within a safety corridor and therefore poses a potential risk to a following aircraft. A simple crosswind criterion with a threshold of 2 m/s provides a safety corridor that is free of wake vortices under radar separation. This demonstrates the large potential for safe reduction of aircraft separation under crosswind conditions. This is supported by an analysis of a wind climatology representative for Frankfurt airport.

Frech, M. and Zinner, T.

"WAKE VORTEX BEHAVIOUR CLASSES AND THEIR INITIAL VALIDATION"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

Experimental and numerical results indicate that existing wake vortex separation standards appear most of the time over-conservative which means that atmospheric conditions often favor a rapid decay and/or transport of wake vortices (WV) out of the glide path corridor. In order to reduce the separation distances a Wake Vortex Prediction System (WVPS) is needed. A WVPS consists of a weather and a WV predictor which forecasts the decay and transport of WVs. The forecasted WV decay and trajectory is then used to re-stagger approaching aircraft if the WV poses no hazard to a following aircraft. This requires a validated wake vortex transport and decay model together with high resolution meteorological input data. Examples for such systems are AVOSS, the wake vortex warning system

(WVWS) at Frankfurt Airport and Syage. For various reasons none of these systems are operational to date. Typically, a real-time wake vortex model requires as meteorological input profiles of the wind components, temperature and turbulent kinetic energy or alternatively eddy dissipation rate. Especially profiles of turbulent kinetic energy are difficult to measure and predict with high vertical resolution in an operational environment. Our new approach is to establish meteorologically motivated 'wake vortex behavior classes' (WVBC) which favor a certain wake vortex evolution with respect to transport and decay out of and in ground effect. Rather than predicting the individual wake vortex trajectory it is suggested to predict the meteorological situation causing a characteristic wake vortex behavior. The WVBC names explicitly refer to their ability to cause a specific wake vortex behavior, namely Rapid Decay - Moderate Decay - Weak Decay - Transport - IGE.

Frech, M., Holzaepfel, F., Gerz, T. and Konopka, J.

"SHORT-TERM PREDICTION OF THE HORIZONTAL WIND VECTOR WITHIN A WAKE VORTEX WARNING SYSTEM"

Meteorological Applications, Vol. 9, 2002, pp. 9-20

A wake vortex warning system (WVWS) has been developed for Frankfurt Airport. This airport has two parallel runways which are separated by 518 m, a distance too short to operate them independently because wake vortices may be advected to the adjacent runway. The objective of the WVWS is to enable operation with reduced separation between two aircraft approaching the parallel runways during appropriate wind conditions. The WVWS applies a statistical persistence model to predict the crosswind within a 20-minute period. One of the main problems identified in the old WVWS is discontinuity between successive forecasts. These forecast breakdowns were not acceptable to air traffic controllers. At least part of the problem was related to the fact that the forecast was solely based on the prediction of crosswind. A new method is developed on the basis of 523 days of sonic anemometer measurements at Frankfurt Airport. It is demonstrated that the prediction of the horizontal wind vector avoids these difficulties and significantly improves the system's performance.

Frech, M., Holzaepfel, F., Tafferner, A. and Gerz, T.

"HIGH-RESOLUTION WEATHER DATABASE FOR THE TERMINAL AREA OF FRANKFURT AIRPORT"

J. Applied Meteorology and Climatology, Vol. 46, Issue 11, Nov. 2007, pp. 1913-1932

A 1-year meteorological dataset for the terminal area of Frankfurt Airport in Germany has been generated with a numerical weather prediction system to provide a synthetic though realistic database for the evaluation of new operational aircraft arrival procedures and their associated risks. The comparison of the 1-year dataset with a local surface wind climatology indicates that the main climatological features are recovered. A subset of 40 days is validated against measurements from a sound detection and range/radio acoustic sounding system (SODAR/RASS) taken at Frankfurt Airport. The frequency distribution of meteorological parameters, such as wind component perpendicular to the glide path, shear, and thermal stratification, show good agreement with observations. The

magnitude of the turbulent energy dissipation rate near the surface is systematically overestimated, whereas above 100 m the authors find on average a slight underestimation. The analysis of the database with respect to crosswind conditions along the glide path indicates only a time fraction of 12 percent for which the crosswind is above a threshold of 2 m/sec. A similar result is obtained using a grid point near the airport that mimics a wind profiler, which suggests that in a majority of cases, a wind profiler appears sufficient to cover the expected crosswind conditions along the glide path. A simple parameterization to account for the crosswind variability along the glide path is proposed.

Frehlich, R.

"DOPPLER LIDAR MEASUREMENTS OF WINDS AND TURBULENCE IN THE BOUNDARY LAYER"

14th International Symposium for the Advancement of Boundary Layer Remote Sensing, IOP Conf. Series: Earth and Environmental Science, Vol. 1, 2008, pp. 012017-1 to 012017-11.

Coherent Doppler lidar is ideally suited for accurate measurements of the profiles of wind and turbulence using various beam scanning and processing techniques. The most attractive scanning pattern is a three-dimensional pattern which samples the largest number of independent samples of the turbulent field. Careful processing of the radial velocity estimates is required to correct for the spatial filtering by the lidar pulse and to remove the bias introduced by the estimation error. The various processing techniques and fundamental assumptions will be presented. Lidar derived profiles of wind and turbulence will be compared with in situ data, when available. Results will also be presented from a field campaign focused on wind energy applications.

Frehlich, R. and Cornman, L.

"COHERENT DOPPLER LIDAR SIGNAL SPECTRUM WITH WIND TURBULENCE"

Applied Optics, Vol. 38, No. 36, December 1999, pp. 7456-7466.

The average signal spectrum (periodogram) for coherent Doppler lidar is calculated for a turbulent wind field. Simple approximations are compared with the exact calculation. The effects of random errors in the zero-velocity reference, the effects of averaging spectral estimates by use of multiple lidar pulses, and the effects of the range dependence of the lidar signal power over the range gate are included. For high spatial resolution measurements, the lidar signal power is concentrated around one spectral estimate (spectral bin) and correct interpretation of the contribution from turbulence is difficult because of the effects of spectral leakage. For range gates that are larger than the lidar pulse volume, the signal power is contained in many spectral bins and the effects of turbulence can be determined accurately for constant signal power over the range gate and for the far-field range dependence of the signal power.

Frehlich, R. and Kelley, N.

"COHERENT DOPPLER LIDAR FOR WIND ENERGY RESEARCH"

Proceedings 15th Coherent Laser Radar Conference, June 2009, Toulouse, France, pp. 263-266.

Wind energy has become an important new and rapidly growing source of renewable energy. However, many issues for efficient energy production and use of wind energy are unresolved. Wind resource assessment requires accurate profiles of both the wind speed and turbulence statistics to identify the most promising locations for efficient wind production with minimal damage to the turbines from high shear and turbulence. Optimal control of the turbine blades requires high quality wind information upstream of a wind farm or at each individual turbine. Accurate short-term forecasts of power production require accurate wind profiles at various distances upstream of the wind farm. Scanning coherent Doppler lidar is the most attractive instrument for high quality measurements of the wind fields for the conditions of interest for wind energy research. New results are presented from a field campaign at the National Wind Technology Center to evaluate coherent Doppler lidar for wind energy research. Lidar derived wind and turbulence estimates are compared with results from a nearby instrumented tower for various conditions.

Frehlich, R. and Sharman, R.

"MAXIMUM LIKELIHOOD ESTIMATES OF VORTEX PARAMETERS FROM SIMULATED COHERENT DOPPLER LIDAR DATA"

Journal of Atmospheric and Oceanic Technology, Vol. 22, February 2005, pp. 117-130

The performance of pulsed coherent Doppler lidar in estimating aircraft trailing wake vortices by scanning across the aircraft flight track is evaluated using Monte Carlo lidar simulations of a simple vortex pair in both a nonturbulent and turbulent environment. The performance estimates are based on maximum likelihood estimates of aircraft wake vortex parameters and provide a measure of the ability of the lidar to detect and track wake vortices under the best possible conditions. Two aircraft types are considered: the Boeing 737 and the Boeing 747. Rigorous error analyses are produced by comparing the estimated parameters from numerical simulations of raw lidar data with the known input parameters of the simulation. It is shown that the probability density functions for the estimates are approximately Gaussian and the bias is very small. The main source of the bias was determined to be the movement of the vortex during the lidar scan. The estimation error is increased by the effects of a background turbulent velocity field. The trade-off between lidar pulse energy and pulse repetition frequency for the standard condition of constant laser power is also presented. It is shown that these maximum likelihood estimates provide accurate detection and tracking of the key vortex parameters for a simple vortex model, with and without background turbulence.

Frehlich, R., Hannon, S. M. and Henderson, S. W.

"PERFORMANCE OF A 2-MICRON COHERENT DOPPLER LIDAR FOR WIND MEASUREMENTS"

Journal of Atmospheric and Oceanic Technology, Vol. 11, December 1994, pp. 1517-1528.

Measurements of boundary layer winds are presented using a 2-micron coherent Doppler lidar and the optimal performance of the maximum likelihood estimator. The systematic error for single-shot

estimates was estimated as 3.6 cm/s using measurements from a stationary hard target. The estimation error for measurements of the radial component of the wind field was determined, as well as the fraction of the estimates that are randomly distributed over the velocity search space, when the signal power is low and speckle fading is important. The results from actual data are compared with the results from ideal simulations. The first direct estimation of the spatial structure function of the radial wind field and of the energy dissipation rate is presented for both horizontal and vertical directions of propagation. The rms estimation error of the velocity estimates is found to be within 30 percent of ideal performance based on simulation.

Frehlich, R., Meillier, Y., Jensen, M. L. and Balsley, B.

"MEASUREMENTS OF BOUNDARY LAYER PROFILES IN AN URBAN ENVIRONMENT"

Journal of Applied Meteorology and Climatology, Vol. 45, 2006, pp. 821-837.

Boundary layer profiles of mean temperature, velocity, and small-scale turbulence from in situ sensors, Doppler lidar, sodar, and rawinsondes are intercompared for an urban environment. A new Doppler lidar algorithm is presented to produce high-resolution profiles of small-scale velocity statistics. The lidar-derived profiles are robust and accurate even for challenging conditions such as stable boundary layers with a low-level jet, low turbulence, and low wind speed. Similar results are expected for other locations and convective conditions.

Freund, D. J. and Vickers, T. K.

"PRELIMINARY TEST PLANS OF ATC CONCEPTS FOR LONGER TERM IMPROVEMENT -- HELICOPTER DEVELOPMENT PROGRAM"

FAA-RD-80-87, May 1980, Automation Industries, Inc., Silver Springs, MD

Test and simulation planning is documented for longer-term improvements in helicopter ATC concepts, which are classified into the following categories: (1) Offshore Route Structure in the Gulf of Mexico, (2) Secondary Radar, (3) Analysis of Navigation Errors in the Gulf, (4) Offshore Surveillance and Communications to 300 NM Range, (5) Real-Time Reporting of Aircraft-Derived Position, (6) VHF Communications Study in the CONUS, (7) ATC Implications of Alternate Airports for Helicopters, and (8) Wake Vortex Separation.

Freville, E., Nicolaon, J.-P., Vidal, A. and Crick, P.

"POTENTIAL BENEFITS OF A TIME-BASED SEPARATION PROCEDURE TO MAINTAIN THE ARRIVAL CAPACITY OF AN AIRPORT IN STRONG HEAD-WIND CONDITIONS"

Fifth EUROCONTROL/FAA ATM R&D Seminar, June 2003, Budapest, Hungary

This paper describes a different approach to separating aircraft during the final approach phase. It is based on the fact that, under strong head-wind conditions (>15kt.), the ground speed of the aircraft is

reduced and so there is a loss of runway capacity. Because of this, each aircraft needs more time to fly a given separation distance at the runway threshold. Under headwind conditions, the actual distance-based separation procedure may thus be not fully satisfactory. Moreover, according to current characterization studies of wake vortices, which are the main hazards limiting capacity, the actual distance separation thresholds have been proved to be too conservative under strong wind conditions. We thus propose to replace the actual distance-based separations by time-based separations. Without reducing safety, such a process could maintain and increase runway capacity in a shorter term than the wake vortex advisory systems that will require more technology before they can be implemented. Let us note that both tools should be used anyway to get optimal and safe separations in the future.

Freythum, P.

"THREE-DIMENSIONAL VORTEX SYSTEMS OF FINITE WINGS"

Journal of Aircraft, Vol. 25, No. 10, October 1988, pp. 971-972

The vortex strands of a finite three-dimensional vortex system must be connected in accordance with Helmholtz's law. It is shown that flow visualization documents the connecting and reconnecting of the strands.

Freythum, P., Finaish, F. and Bank, W.

"VISUALIZATION OF WING TIP VORTICES IN ACCELERATING AND STEADY FLOW"

Journal of Aircraft, Vol. 23, No. 9, September 1986, pp. 730-733

A streakline method was used to visualize complex two- and three-dimensional vortical structures over an airfoil. The method was extended to visualize wing tip vortices in unsteady and steady flows.

Fridman, J. D.

"AIRBORNE WAKE VORTEX DETECTION"

FAA-RD-74-46, March 1974, Raytheon Company, Sudbury, MA

Active and passive remote sensing systems were assessed to determine the feasibility of detecting aircraft trailing vortices using instrumentation on-board an aircraft. It was found that a modification of the front-end receiver of a 10 GHz weather radar system or a change of frequency to 35 GHz may allow vortex identification over a range of several kilometers. The CO₂ laser coherent Doppler radar technique and passive radiometric techniques (8-14 microns) show considerable promise. Other airborne systems (incoherent Lidar, Raman shift techniques, fluorescence scattering, acoustic radar, ultraviolet emissions) were shown not to possess sufficient sensitivity.

Fridman, J. D. and Hallock, J. N.

"AIRBORNE WAKE VORTEX DETECTION"

Proceedings of the Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorological Society, 1974, pp. 399-404.

Active and passive remote sensing systems have been assessed to determine the feasibility of detecting aircraft trailing vortices using instrumentation on-board an aircraft. A front-end modified millimetric wave weather radar may allow vortex identification over a range of several kilometers for a sufficiently large target cross-section. A 10.6-micron coherent Doppler optical radar detects the presence of a trailing vortex over a range of several miles. A passive radiometric technique in the 8-14 micron range also shows considerable promise.

Friebel, H. C., Herrington, T. O. and Benilov, A. Y.

"EVALUATION OF THE FLOW DISTORTION AROUND THE CAMPBELL SCIENTIFIC CSAT3 SONIC ANEMOMETER RELATIVE TO INCIDENT WIND DIRECTION"

Journal of Atmospheric and Oceanic Technology, Vol. 26, March 2009, pp. 582-592.

In June 2002, a high-frequency air-sea momentum system was deployed in the surf zone for 3 days as part of an experiment to quantify air-sea momentum transfer when the wind and wave direction were at angles. The system obtained measurements in the nearshore via a high-resolution Campbell Scientific CSAT3 3D sonic anemometer and five high-frequency saltwater wave staffs. An advantage of the air-sea momentum system is that direct measurements of the atmospheric turbulent fluctuations can be obtained and applied to the calculation of momentum transfer at the air-sea interface. The Campbell Scientific CSAT3 sonic anemometer was post-calibrated under turbulent wind conditions to determine incident wind direction measurements influenced by the geometry of the instrument. Measurement results are compared to a pre-established benchmark, constant tow speed, and the mean wind speed, incident wind direction, and spectral density characteristics are evaluated to resolve specific instrument orientations in which the measurements are corrupted by the head and probe supports of the sonic anemometer.

Friedlander, S.

"ON VORTEX TUBE STRETCHING AND INSTABILITIES IN AN INVISCID FLUID"

Journal of Mathematical Fluid Mechanics, Vol. 4, No. 1, February 2002, pp. 30-40

We study instabilities that are present in two models that retain some of the dynamics of vortex tube stretching in the motion of a fluid in 3 dimensions. Both models are governed by a 2-dimensional PDE and are hence more tractable than the full 3-dimensional Euler equations. The first model is the so-called surface quasi-geostrophic equation. The second model is a class of 3-dimensional flows that are invariant with respect to one spatial coordinate. Both models appear in the context of a rapidly rotating fluid. Instabilities due to an effect analogous to vortex tube stretching are detected: these

instabilities are in the linearized equations in the first model and in the nonlinear equations in the second model. Such instabilities are absent, or weaker, in strictly 2-dimensional fluid motion.

Friedrich, K., Lundquist, J. K., Aitken, M., Kalina, E. A. and Marshall, Robert F.

"STABILITY AND TUBULENCE IN THE ATMOSPHERIC BOUNDARY LAYER: A COMPARISON OF REMOTE SENSING AND TOWER OBSERVATIONS"

Geophysical Research Letters, Vol. 39, 2012, pp. L03801-L03801-6.

When monitoring winds and atmospheric stability for wind energy applications, remote sensing instruments present some advantages to in-situ instrumentation such as larger vertical extent, in some cases easy installation and maintenance, measurements of vertical humidity profiles throughout the boundary layer, and no restrictions on prevailing wind direction. In this study, we compare remote sensing devices, Windcube lidar and microwave radiometer, to meteorological in-situ tower measurements to demonstrate the accuracy of these measurements and to assess the utility of the remote sensing instruments in overcoming tower limitations. We compare temperature and wind observations, as well as calculations of Brunt-Vaisala frequency and Richardson numbers for the instrument deployment period in May-June 2011 at the U.S. Department of Energy National Renewable Energy Laboratory's National Wind Technology Center near Boulder, Colorado. The study reveals that a lidar and radiometer measure wind and temperature with the same accuracy as tower instruments, while also providing advantages for monitoring stability and turbulence. We demonstrate that the atmospheric stability is determined more accurately when the liquid-water mixing ratio derived from the vertical humidity profile is considered under moist-adiabatic conditions.

Frink Jr., W. D.

"HOT-WIRE SURVEYS IN THE VORTEX WAKE DOWNSTREAM OF A THREE-PERCENT FIGHTER AIRCRAFT MODEL AT HIGH ANGLES OF ATTACK"

MS Thesis, Dec. 1990, Naval Postgraduate School, Monterey, CA.

A low-speed wind tunnel investigation was conducted to examine the vortex wake downstream of a three-percent scale model of the YF-17 lightweight fighter prototype at high angles of attack. The study was in support of NASA Ames Research Center's High Alpha Technology Program. Smoke flow visualization was used to locate the downstream vortex wake. Hot-wire surveys were taken through the vortex at two stations; one directly aft of the model and the other at a station three model lengths downstream of the model. The effect of adding a fence to the leading-edge extension was studied. Power spectra from the hot-wire were recorded for the survey station directly aft of the model. Results show that peak turbulent fluctuation at this station occurred at 25 degrees angle of attack, lateral turbulent fluctuation greatly diminished at the far downstream station, and the addition of the leading-edge extension fence shifted energy content of turbulence toward higher frequencies.

Friso, H. F., Richard, C., Visser, H. G., Vincent, T. and Bruno, D.

"PREDICTING ABNORMAL RUNWAY OCCUPANCY TIMES AND OBSERVING RELATED PRECURSORS"

Journal of Aerospace Information Systems, Vol. 15, No. 1, January 2018, pp. 10-21.

Accidents on the runway triggered the development and implementation of mitigation strategies. Therefore, the airline industry is moving toward proactive risk management, which also aims to identify and predict risk precursors and to mitigate risks before accidents occur. For certain predictions machine learning techniques can be used. Although many studies have explored and applied novel machine learning techniques on different radar and A-SMGCS data, the identification and prediction of abnormal runway occupancy times and the observation of related precursors are not well developed. In our previous papers, three existing methods were introduced, lasso, multi-layer perception, and neural networks, to predict the taxi-out time on the taxiway and the time to fly and true airspeed profile on final approach. This paper presents a new machine learning method where the existing machine learning techniques are combined for predicting the abnormal runway occupancy times of unique radar data patterns. Additionally, the regression tree method is used in this study to observe the key related precursors extracted from the top 10 features. Compared with existing methods, the new method no longer requires predefined criteria or domain knowledge. Tests were conducted using final approach radar data and A-SMGCS runway data consisting of 78,321 flights at Paris Charles de Gaulle airport and were benchmarked against 500,000 flights at Vienna airport.

Frith, S. P. and Wood, N. J.

"THE USE OF CIRCULATION CONTROL FOR FLIGHT CONTROL"

Circulation Control Workshop, Hampton, VA, March 2004, pp. 657-674

An experimental investigation into the application of circulation control on a 50-degree swept delta wing has been performed in a closed return wind tunnel at 25 m/s. This was then extended to a sting-mounted circulation control demonstrator with two control surfaces, in order to determine whether the technique could be used for roll control whilst maintaining high lift coefficient within the limits of pitch trim. A lift augmentation of approximately 20 was achieved with all configurations. Roll of the aircraft was possible with differential blowing of the circulation control systems.

Fritz, T. E. and Long, L. N.

"OBJECT-ORIENTED UNSTEADY VORTEX LATTICE METHOD FOR FLAPPING FLIGHT"

Journal of Aircraft, Vol. 41, No. 6, November-December 2004, pp. 1275-1290.

The unsteady vortex lattice method is used to model the oscillating plunging, pitching, twisting, and flapping motions of a finite-aspect-ratio wing. Its potential applications include design and analysis of small unmanned air vehicles and in the study of the high-frequency flapping flight of birds and other small flyers. The results are verified by theory and, in the plunging and pitching cases, by experimental data. The model includes free-wake relaxation, vortex stretching, and vortex dissipation effects and is

implemented using object-oriented computing techniques. The results show that the method is capable of accurately simulating many of the features of complex flapping flight.

Frohlingsdorf, W. and Unger, H.

"NUMERICAL INVESTIGATIONS OF THE COMPRESSIBLE FLOW AND THE ENERGY SEPARATION IN THE RANQUE-HILSCH VORTEX TUBE"

International Journal of Heat and Mass Transfer, Vol. 42, 1999, pp. 415-422.

In the Ranque-Hilsch vortex tube a compressible fluid (e.g., air) experiences an expansion process leading to separation into a cold and hot gas stream. The compressible flow and energy separation phenomena are simulated numerically by using the code system CFX. In order to calculate successfully the energy separation, the numerical model had to be extended by integrating relevant terms for the shear-stress-induced mechanical work. An axisymmetric model was developed, allowing a successful post-calculation of experimental results.

Fucke, L. and Luckner, R.

"OPTIMIZING MOTION CUEING FOR RESEARCH FLIGHT SIMULATION"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-330, September 2007, pp. 1305-1313

Research flight simulation conducted with the A330/340 Full-Flight Simulator located at Technical University Berlin exceeds the typical flight envelope of airline pilot training. For such simulator studies a motion cueing algorithm optimized for the research task should provide improved motion reproduction. As one of the potential applications the specific motion system requirements of wake vortex encounter simulation are analyzed. An optimized setting of the motion cueing algorithm is derived and implemented into the simulator motion system. To conclude, results of a piloted test campaign are presented, in which the effect of simulator motion on perceived severity of wake vortex encounters and pilot reaction were studied by comparing results for a motion cueing setup as used for pilot training, a setup optimized for wake vortex encounter simulation and wake encounters conducted without simulator motion.

Fuentes, O. U. V.

"ON THE TOPOLOGY OF VORTEX LINES AND TUBES"

J. Fluid Mechanics, Vol. 584, 2007, pp. 147-156.

This paper examines the widespread idea that vortex lines and tubes must either close on themselves or extend to the boundary of the fluid. A survey of the origins of this misconception, and of earlier attempts to set it right, is followed by an analysis of simple flows exhibiting vortex lines and tubes which do not fit those shapes. Two types of vortex lines are discussed: dense, which comprise open

lines of infinite length but confined in a finite region, and separatrix, which comprise lines that begin or finish within the fluid, at points where the vorticity is null. The presence of these vortex lines in a vortex tube affects its topology in the following ways: Vortex tubes formed by dense vortex lines have infinite length; they self-intersect an infinite number of times but do not close on themselves. Vortex tubes formed by separatrix vortex lines (and either closed or open vortex lines) are torn apart at the points where the vorticity is null. Vortex tubes exclusively composed of separatrix vortex lines begin or finish at points or surfaces within the fluid; in this particular situation, the vortex tube has zero strength.

Fuentes, O. V. and Arteaga, A. R.

"QUASI-STEADY LINKED VORTICES WITH CHAOTIC STREAMLINES"

Journal of Fluid Mechanics, Vol. 687, 2011, pp. 571-583.

This paper describes the motion and the flow geometry of two or more linked ring vortices in an otherwise quiescent, ideal fluid. The vortices are thin tubes of near-circular shape which lie on the surface of an immaterial torus of small aspect ratio. Since the vortices are assumed to be identical and evenly distributed on any meridional section of the torus, the flow evolution depends only on the number of vortices (n) and the torus aspect ratio (r_1/r_0 , where r_0 is the centerline radius and r_1 is the cross-section radius). Numerical simulations based on the Biot-Savart law showed that a small number of vortices ($n = 2, 3$) coiled on a thin torus (r_1/r_0 less than or equal to 0.16) progressed along and rotated around the symmetry axis of the torus in an almost uniform manner while each vortex approximately preserved its shape. In the comoving frame the velocity field always possesses two stagnation points. The transverse intersection, along $2n$ streamlines, of the stream tube emanating from the front stagnation point and the stream tube ending at the rear stagnation point creates a three-dimensional chaotic tangle. It was found that the volume of the chaotic region increases with increasing torus aspect ratio and decreasing number of vortices.

Fuhrmann, H. D. and Stewart, E. C.

"AN EVALUATION OF THE MEASUREMENT REQUIREMENTS FOR AN IN-SITU WAKE VORTEX DETECTION SYSTEM"

NASA TM-110218, May 1996, Langley Research Center, Hampton, VA

Results of a numerical simulation are presented to determine the feasibility of estimating the location and strength of a wake vortex from imperfect in-situ measurements. These estimates could be used to provide information to a pilot on how to avoid a hazardous wake vortex encounter. An iterative algorithm based on the method of secants was used to solve the four simultaneous equations describing the two-dimensional flow field around a pair of parallel counter-rotating vortices of equal and constant strength. The flow field information used by the algorithm could be derived from measurements from the flow angle sensors mounted on the wing tips of the detecting aircraft and an inertial navigation system. The study determined the propagated errors in the estimated location and

strength of the vortex which resulted from random errors added to theoretically perfect measurements. The results are summarized in a series of charts and a table which make it possible to estimate these propagated errors for many practical situations. The situations include several generator-detector-airplane combinations, different distances between the vortex and the detector airplane, as well as different levels of total measurement error.

Fujimura, K., Koyama, H. S. and Hyun, J. M.

"AN EXPERIMENTAL STUDY ON VORTEX BREAKDOWN IN A DIFFERENTIALLY-ROTATING CYLINDRICAL CONTAINER"

Experiments in Fluids, Vol. 36, 2004, pp. 399-407

The vortex breakdown phenomenon in a closed cylindrical container with a rotating end-wall disk was reproduced. Visualizations were performed to capture the prominent flow characteristics. The locations of the stagnation points of breakdown bubbles and the attendant global flow features were in excellent agreement with the preceding observations. Experiments were also carried out in a differentially-rotating cylindrical container in which the top end-wall rotates at a relatively high angular velocity and the bottom end-wall and the sidewall rotate at a low angular velocity. For a fixed cylinder aspect ratio, and for a given relative rotational Reynolds number based on the angular velocity difference the flow behavior is examined as the Reynolds number increases. For a co-rotation, the breakdown bubble is located closer to the bottom end-wall disk. However, for a counter-rotation, the bubble is seen closer to the top end-wall disk. For sufficiently large values the bubble ceases to exist for both cases.

Fukumoto, Y.

"THE THREE-DIMENSIONAL INSTABILITY OF A STRAINED VORTEX TUBE REVISITED"

J. Fluid Mech., Vol. 493, 2003, pp. 287-318.

We revisit the Moore-Saffman-Tsai-Widnall instability, a parametric resonance between left- and right-handed bending waves of infinitesimal amplitude, on the Rankine vortex strained by a weak pure shear flow. The results of Tsai and Widnall (1976) and Eloy and Le Dizès (2001), as generalized to all pairs of Kelvin waves whose azimuthal wavenumbers m are separated by 2, are simplified by providing an explicit solution of the linearized Euler equations for the disturbance flow field. Given the wavenumber k and the frequency ω of an intersection point of dispersion curves, the growth rate is expressible solely in terms of the modified Bessel functions, and so is the unstable wavenumber range. Every intersection leads to instability. Most of the intersections correspond to weak instability that vanishes in the short-wave limit, and dominant modes are restricted to particular intersections. For helical waves $m = \pm 1$, the growth rate of non-rotating waves is far larger than that of rotating waves. The wavenumber width of stationary instability bands broadens linearly in k , while that of rotating instability bands is bounded. The growth rate of the stationary instability takes, in the long-wavelength limit, the value of $E/2$ for the two-dimensional displacement instability, and, in the short-

wavelength limit, the value of $9E/16$ for the elliptical instability, being larger at large but finite values of k . Here E is the strength of shear near the core center. For resonance between higher azimuthal wavenumbers m and $m + 2$, the same limiting value is approached as k goes to infinity, along sequences of specific crossing points whose frequency rapidly converges to $m + 1$. This happens in two ways, from above for a fixed m and from below for m going to infinity. The energy of the Kelvin waves is calculated by invoking Cairns' formula. The instability result is compatible with Krein's theory for Hamiltonian spectra.

Fukumoto, Y. and Hattori, Y.

"CURVATURE INSTABILITY OF A VORTEX RING"

J. Fluid Mech., Vol. 526, 2005, pp. 77-115

A global stability analysis of Kelvin's vortex ring to three-dimensional disturbances of infinitesimal amplitude is made. The basic state is a steady asymptotic solution of the Euler equations, in powers of the ratio r of the core radius to the ring radius, for an axisymmetric vortex ring with vorticity proportional to the distance from the symmetric axis. The effect of ring curvature appears at first order, in the form of a dipole field, and a local straining field, which is a quadrupole field, follows at second order. The eigenvalue problem of the Euler equations, retaining the terms to first order, is solved in closed form, in terms of the Bessel and the modified Bessel functions. We show that the dipole field causes a parametric resonance instability between a pair of Kelvin waves whose azimuthal wavenumbers are separated by 1. The most unstable mode occurs in the short-wavelength limit, under the constraint that the radial and the azimuthal wavenumbers are of the same magnitude, and the limiting value of maximum growth rate coincides with the value $165/256r$ obtained by Hattori and Fukumoto (Phys. Fluids, vol. 15, 2003, p. 3151) by means of the geometric optics method. The instability mechanism is traced to stretching of disturbance vorticity in the toroidal direction. In the absence of viscosity, the dipole effect outweighs the straining field effect known as the Moore-Saffman-Tsai-Widnall instability. The viscosity acts to damp the former preferentially and these effects compete with each other.

Fukumoto, Y. and Hattori, Y.

"LINEAR AND NONLINEAR INSTABILITY OF A VORTEX RING"

In IUTAM Symposium on Elementary Vortices and Coherent Structures: Significance in Turbulence Dynamics, edited by S. Kida, Springer, The Netherlands, 2006, pp. 283-294.

A new linear instability mechanism of curvature origin is established for a vortex ring. The curvature effect reduces $O(2) \times SO(2)$ symmetry of a circular-cylindrical tube to $O(2)$, and fuels a pair of Kelvin waves whose azimuthal wavenumbers on the core are separated by one. For Kelvin's vortex ring, the growth rate and eigenfunctions are written out in closed form. In the inviscid case, the curvature effect dominates over the elliptically straining effect, but the former suffers from enhanced viscous damping. There are numerous excitable modes. As a first step toward an understanding of the route to a

matured stage, we derive equations for weakly nonlinear evolution of amplitudes of the curvature instability. One direct numerical simulation successfully captures the elliptical instability.

Fukumoto, Y. and Moffatt, H. K.

"MOTION OF A THIN VORTEX RING IN A VISCOUS FLUID: HIGHER-ORDER ASYMPTOTICS"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

The motion of an axisymmetric vortex ring of small cross-section in a viscous incompressible fluid is investigated using a large-Reynolds-number asymptotic theory. Tung and Ting and Saffman considered the effect of decaying core vorticity due to the action of viscosity. The vortex ring induces a local straining field on itself which deforms the core into an ellipse. The purpose of the present investigation is to elucidate the structure of strained core and its influence on the translation speed.

Fukumoto, Y. and Okulov, V. L.

"THE VELOCITY FIELD INDUCED BY A HELICAL VORTEX TUBE"

Physics of Fluids, Vol. 17, 2005, 107101-1 to 107101-19

The influence of finite-core thickness on the velocity field around a vortex tube is addressed. An asymptotic expansion of the Biot-Savart law is made to a higher order in a small parameter, the ratio of core radius to curvature radius, which consists of the velocity field due to lines of monopoles and dipoles arranged on the centerline of the tube. The former is associated with an infinitely thin core and is featured by the circulation alone. The distribution of vorticity in the core reflects on the strength of dipole. This result is applied to a helical vortex tube, and the induced velocity due to a helical filament of the dipoles is obtained in the form of the Kapteyn series, which augments Hardin's [Phys. Fluids 25, 1949 (1982)] solution for the monopoles. Using a singularity-separation technique, a substantial part of the series is represented in a closed form for both the mono- and the dipoles. It is found from numerical calculation that the smaller the helix pitch is, the larger the relative influence of the dipoles is as the cylinder wound by the helix is approached.

Fuller, C. E.

"A STUDY OF TURBULENCE MEASUREMENTS USING LASER DOPPLER SYSTEM"

NASA CR-119804, June 1971, Remtech Inc., Birmingham, AL

The object of the wing tip vortex test is to demonstrate the extent with which the Laser Doppler Velocimeter system can be used for the measurement of gas velocities with high spatial and temporal resolution. This test was planned to provide three-dimensional mean velocity data of the vortex pattern shed from a wing tip at an angle of attack. These measurements are being conducted at the MSFC 7inch x 7inch wind tunnel facility. The test plan and procedure as well as the measurements that

were made are included. In addition, data on several measurements of the system's operating parameters which are important to these tests are also given.

Fuller, C. E.

"WING TIP DOPPLER MEASUREMENTS WITH LASER DOPPLER SYSTEMS"

RTR-002-3, April 1973, Remtech Inc., Huntsville, AL

The vortex velocity field produced by a rectangular wing in a subsonic wind tunnel was measured using two laser Doppler velocimeter systems. One system made three-dimensional mean velocity measurements and the other made one-dimensional turbulence measurements. The systems and test procedures are described and the measurements are presented and comparisons made. The data defined a strong spiral motion in the vortex- formation process.

Funk, B. H. and Johnston, K. D.

"LASER NET - A SYSTEM FOR MONITORING WINGTIP VORTICES ON RUNWAYS"

NASA TM X-64525, June 1970, NASA Marshall Space Flight Center, Huntsville, AL

A laser schlieren method is proposed which potentially provides a means for monitoring the strength of vortex wakes on and near runways. The method could provide a gross, continuous assessment of the intensity of disturbances over airport runways and aircraft carriers. Preliminary measurements behind a wingtip mounted on the wall of a small subsonic wind tunnel indicate that wingtip vortices are readily detectable with this simple system.

Funk, R. B. and Komerath, N. M.

"ROTOR WAKE INTERACTION WITH A LIFTING SURFACE"

51st Annual Forum of the American Helicopter Society, May 1995, Ft. Worth, TX.

Vortex interaction with wings and control surfaces causes unsteady, three-dimensional flow separation phenomena which are only beginning to be understood. An NACA0021 wing interacting with the wake from a 2-bladed teetering rotor is used as a basic experimental configuration to study such phenomena. Video images of surface tufts and smoke in pulsed light sheets, laser velocimetry and surface pressure sensors are used to capture the primary features of the interaction. The interaction is found to be periodic except during the impingement of the vortices on the surface. Strong once-per-revolution pressure fluctuations are shown to result from the divergence of vortex trajectories, enhanced by surface interaction. Flow reversal is found upstream and under regions of vortex interaction on the wing upper surface, and massive steady separation is found on the lower surface. Vortex core flow stagnation on the surface under the advancing blade side appears to cause an apparent 'diffusion' of vorticity seen in vorticity contours constructed from velocity data. Strong, quasi-steady spanwise flow is caused downstream of vortex interaction. The separation line moves rapidly

over the surface. Integrated section pressure distributions are dominated by the blade passage signature, periodic at the blade frequency.

Funk, R. B., Fawcett, P. A. and Komerath, N. M.

"SCV MEASUREMENTS IN THE WAKE OF A ROTOR IN HOVER AND FORWARD FLIGHT"

AIAA Paper 93-3080, July 1993, Orlando, FL.

Progress in the capability to measure instantaneous velocity fields in complex flows and over large areas is discussed. The rotor wake is a complex flow field containing a wide range of velocity scales that exhibit a periodic variation with rotor azimuth. The measurement of instantaneous planar velocity fields over large areas in such flows is demonstrated using Spatial Correlation Velocimetry. A dual video camera system is used to obtain images over short intervals, with velocities computed using a fully numerical procedure. Results are presented for twelve azimuth positions in the wake of a 2-bladed teetering rotor of 0.457 m radius, at 1050 rpm in low-speed forward flight, with smoke in the flow illuminated using a pulsed laser sheet. Detection of a roll-up under the rotor hub is discussed. A second area of application is shown in the measurement of turbulence statistics in recirculating flows over large areas. The recirculating flow in a 4.88 m rotor hover test facility is measured piecewise. Ensemble-averaging of local mean and root-mean-square velocity components is presented, with incoherent light sheets created from quartz lamps. Problems encountered and possible solutions are also discussed.

Funston, N. L. and Koob, S. L.

"A TRAILING VORTEX MODEL AND ITS EFFECT ON A PENETRATING AIRCRAFT"

Proceedings of the National Aerospace Electronics Conf., IEEE, 1971, pp. 23-27

The high strength of the trailing vortex system produced by the new jumbo jet aircraft has renewed interest in the study of the vortex phenomenon and its effect on proximate aircraft operations. In the present study, the trailing vortex system produced by an aircraft in flight and penetration of the system by a second aircraft are modeled mathematically. The effect of turbulent mixing on the persistence of the intact trailing vortices is modeled by modifying the similar solution for a decaying laminar vortex. The correction is made by introducing an effective turbulent viscosity which is determined empirically. The vortex induced velocity is superimposed on the free stream velocity of a penetrating aircraft to determine a total velocity vector and angle of attack history. Separation times and distances required for safe operation in traffic pattern conditions are predicted using a gust load formula and maximum incremental load factors. Calculations were performed for several generator/penetrator aircraft combinations.

Gados, R. G. and Amodeo, F. A.

"PROCEDURAL FEASIBILITY OF REDUCED SPACING UNDER WAKE VORTEX AVOIDANCE SYSTEM OPERATION, WITH APPLICATIONS TO ATLANTA AND O'HARE"

FAA-EM-79-18, August 1979, Mitre Corp., McLean, VA.

A Wake Vortex Avoidance System (WVAS) may provide increased airport capacity by allowing for reduced aircraft separation standards on final approach under certain meteorological conditions. Three sets of reduced separation standards have been hypothesized to describe the operational characteristics of potential WVAS systems. Analyses develop several operational schemes which allow aircraft to transition to reduced separation standards when under WVAS coverage, while maintaining larger terminal area standards prior to intercepting that coverage. Specific applications of these schemes to Atlanta Hartsfield and Chicago O'Hare International Airports are also described. Other analyses investigate procedures for and dynamics of transitioning between different sets of separation standards. Capacity benefits corresponding to the utilization of the different sets of separation standards, under various operational procedures, are estimated for Chicago and Atlanta.

Gago, C. F., Brunet, S. and Garnier, F.

"NUMERICAL INVESTIGATION OF TURBULENT MIXING IN A JET/WAKE VORTEX INTERACTION"

AIAA Journal, Vol. 40, No. 2, 2002, pp. 276-284

A three-dimensional temporal numerical simulation of the interaction between a jet and a vortex wake is described to contribute to the understanding and modeling of engine jet dispersion of an aircraft in cruise condition. First, a comparison of the numerical results with a wind-tunnel experiment is presented. Experimental data comprise turbulent rates measured by a laser Doppler velocimeter and mean temperature fields delivered by thermocouples. The calculation is in quite good agreement with the experiment. Second, the passive scalar distribution (initially included in the jet) in the vortex wake is focused on. The turbulence induced by the jet flow field interacts with the vortex, resulting in large-scale structures generated outside the vortex core, whereas the region very close to the core keeps its laminar state. The passive scalar concentrates in the large-scale structures where azimuthal and axial (positive and negative) vortices are combined. The resulting scalar field distribution shows no scalar inside the vortex core.

Gaifullin, A. M.

"EQUATIONS FOR THE SINUOUS INSTABILITY GROWTH DOWNSTREAM AN AIRCRAFT"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 148-161

Equations have been derived governing variation of sinuous disturbances' amplitude in aircraft vortex wakes. The wake sinuous instability has been studied in response to the frequency of disturbing factors, ground vicinity and parameters of turbulent atmosphere.

Gaifullin, A. M.

"EQUATIONS OF PERTURBATION GROWTH IN AIRCRAFT WAKES"

Fluid Dynamics, Vol. 36, No. 3, 2001, pp. 448-457

Equations for the perturbation amplitude in the vortex wake of an aircraft with a high-aspect-ratio wing are derived. The effect of the perturbing factor frequency, the proximity of the ground, and the turbulent atmosphere characteristics on the wake evolution is investigated.

Gaifullin, A. M.

"EQUATIONS OF PERTURBATION GROWTH IN AIRCRAFT WAKES"

Fluid Dynamic, Vol. 36, No. 3, 2001, pp. 448-457.

Equations for the perturbation amplitude in the vortex wake of an aircraft with a high-aspect-ratio wing are derived. The effect of the perturbing factor frequency, the proximity of the ground, and the turbulent atmospheric characteristics on the wake evolution is investigated.

Gaifullin, A. M. and Gadzhiev, D. A.

"EVOLUTION OF VORTEX WAKE NEAR THE EARTH'S SURFACE"

International Conference on the Methods of Aerophysical Research (ICMAR 2016), AIP Conference Proceedings, Vol. 1770, 2016, pp. 020019-1 to 020019-8.

The evolution of the vortex wake behind an aircraft near the Earth's surface is considered. The problem of diffusion of two discrete vortices near a solid surface is solved.

Gaifullin, A. M. and Soudakov, G. G.

"FROZEN FIELD AND QUASI-STEADY HYPOTHESIS IN THE VORTEX-AIRFOIL INTERACTION PROBLEM"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 132-137

A 'frozen' wake model and a quasi-steady approximation are often used in flight-dynamics and structural-strength studies. This paper is devoted to the evaluation of the accuracy of these models. For this purpose, a 2D problem on the interaction of a vortex cluster with an airfoil is solved. Four related problems were considered: full formulation, problem 'frozen' field model approximation with a vortex cluster, moving together, quasi-stationary approximation which includes the 'frozen' field model combined with the absence of time derivatives in pressure calculations and with the absence of the vortex sheet shedding from the airfoil trailing edge. Comparison of the models shows that the 'frozen' field model gives about 50% errors and quasi-stationary model gives about 100% errors but only in a

short period of time. This discrepancy is of great importance for elasticity analysis because of short period of vibration excitation.

Gaifullin, A. M. and Soudakov, G. G.

"DYNAMICS OF THE WAKE BEHIND AN AIRCRAFT"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 109-118

The paper deals with the problem of wake behavior behind an aircraft in a steady-state formulation. Taken as a wake model is the tangential velocity discontinuity surface. As the transverse wake size at sufficiently large distances from the aircraft is much greater than the streamwise one, an asymptotic approach is used. To first approximation, the well-known unsteady analogy is obtained which fails to describe such phenomena as Crow's instability and wake breakdown. Hence, in this paper the second and, partially, third approximations have been constructed of the solution to the wake dynamics problem. The equations therewith obtained for vortex sheet evolution contain the terms proportional to wake curvature that describe the mechanism of wake breakdown. Studied in detail are the problems on a single vortex filament and two vortex filaments with circulations different in sign. It turned out that besides trivial solutions to these problems, there exist steady-state solutions, exponentially growing along the longitudinal x-axis with the presence of oscillations in the cross-flow plane and without the oscillations as well as neutrally oscillating solutions. The trivial solution for two vortex filaments being unstable, the solutions obtained in this work can be considered as a limit to which the trivial solution goes. [In Russian.]

Gaifullin, A. M. and Soudakov, G. G.

"AIRCRAFT VORTEX WAKE DYNAMICS"

SAE Paper No. 965547, Los Angeles, CA, October 1996

The work deals with the problem on aircraft vortex wake behavior in steady-flow formulation. Further approximations of slender-body theory are constructed with the aid of asymptotic methods. The mathematical approach proposed performs to calculate the aircraft wake up to breakdown. The nontrivial analytic solutions for the problem of motion of one and two vortex filaments with circular cross-section are obtained.

Gaifullin, A. M. and Sviridenko, Y. N.

"DYNAMICS OF THE AIRCRAFT IN A VORTEX WAKE"

Heat and Mass Transfer and Hydrodynamics in Swirling Flows, published in IOP Journal of Physics: Conference Series, Vol. 980, 2018, pp. 012005-1 to 012005-6.

This paper considers the aerodynamics and the dynamics of an aircraft on various modes when the aircraft enters a strongly swirling flow. This is the case when an aircraft purposefully enters the jet-vortex wake of another aircraft during in-flight refueling, when an aircraft is flying in the trail of an aircraft carrier during landing, or when an aircraft accidentally enters other aircrafts' vortex wakes. These situations, according to pilots' evaluation, are the most dangerous and the most difficult modes for piloting. That is why their real time modelling on flight simulators has taken on particular importance. This article provides the algorithms and methodology of mathematical modelling of aerodynamic forces and moments which act upon an aircraft in vortex wakes.

Gaifullin, A. M. and Zoubtsov, A. V.

"ON DIFFUSION OF TWO VORTICES"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 102-112

A two-dimensional problem on the diffusion of two vortices with the intensities $\pm \Gamma$ and spacing $2l$ at the initial instant of time has been considered. The case of high Reynolds numbers $Re \gg 1$ has been investigated. It is shown that at $0 < T \ll Re$ ($T = t\Gamma / (l^2)$) the diffusion process becomes localized in the neighborhood of the vortices' centers. Vorticity distribution in these limited regions is non-axisymmetric in nature, which is responsible for the appearance in the external flow field ($r \sim l$) of unsteady potential disturbances from two multipoles of time-varying strength. The influence of these disturbances on the shape of the boundary of a cluster evolved in the course of the two vortices' self-induced motion has been studied. The vorticity distribution in the main flow region has been investigated. The diffusion process has been shown to be limited, to a first approximation, by a zone where streamlines are closed, whereas outside this zone, the azimuthal component of the velocity is zero.

Gaifullin, A. M. and Zubtsov, A. V.

"DIFFUSION OF TWO VORTICES"

Fluid Dynamics, Vol. 39, No. 1, 2004, pp. 112-127

The problem of the diffusion of two vortices with circulations of opposite sign is considered. An asymptotic solution of the problem is constructed for large Reynolds numbers. The vortex circulation dissipation mechanism is discussed. The results of the analytic investigation are compared with the results of numerical solution of the Navier-Stokes equations.

Gaifullin, A. M., Soudakov, G. G., Voyevodin, A. V. and Zakharov, S. B.

"COMPUTATION OF FLOW IN THE WAKE BEHIND A HIGH-ASPECT-RATIO WING"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 33-42

This work is devoted to studying the aircraft vortex wake using a zonal approach. The whole flow field is subdivided into several zones: the aircraft's neighborhood, near wake, far wake and turbulent core. For each zone, corresponding equations are solved. Numerical matching is performed on the zones' boundaries. In the turbulent core an algebraic turbulence model is used. These computational results agree well with data obtained by use of empirical formulas or experimentally.

Gaifullin, A. M., Voyevodin, A. V. and Zakharov, S. B.

"ZONAL METHOD OF AIRCRAFT WAKE CALCULATION"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 111-120

Basic factors are singled out that influence the structure of the vortex wake and its lifetime: spanwise circulation distribution, turbulent structure of the vortex core, air turbulence properties, vortex merging, circulation loss in the vortices, sinuous disturbances. Main modules of the software package ZONWAKE are described which allow calculation of the wake flow characteristics. Computed results of the B747-400 aircraft are presented.

Gaifullin, A. M., Voyevodin, A. V. and Zakharov, S. B.

"CALCULATION OF THE EVOLUTION OF THE NEAR WAKE BEHIND A HIGH-LIFT WING IN WIND-TUNNEL EXPERIMENT"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 34-38

A version of the ZONWAKE algorithm has been developed, which allows one to numerically investigate the evolution of the near wake behind a wing with high-lift devices, taking into consideration the wall interference of a rectangular cross-section wind tunnel. Computations of the vortex wake were performed in both unconstrained flow and in the presence of solid boundaries. A comparison was conducted between computed data and experimental results obtained in TsAGI's T-124 wind-tunnel.

Gaifullin, A., Korniyakov, A. and Sviridenko, Y.

"REAL TIME MATHEMATICAL MODELING OF THE AERODYNAMIC CHARACTERISTICS OF AN AIRCRAFT ENCOUNTERING VORTEX WAKES"

ICAS Paper 2010-10.3.3, September 2010, Nice, France.

The work describes formation and evolution of vortex street turbulence behind an aircraft in a turbulent atmosphere. It suggests the approach to creation of a mathematical model of aircraft aerodynamics in the in-flight refueling mode based on the use of artificial neural networks. Accuracy appraisal and response time of program modules of the flight simulator software assessment when simulating aerial refueling have been conducted. The main purpose of this work is to develop program modules of software of an aviation training device or a flight simulator when the aerial refueling is simulated. IL-78 is considered as an aerial tanker and IL-76 as a receiver aircraft. During the in-flight refueling the receiver aircraft is subjected to the nonhomogeneous field of velocities caused by the jet vortex wake of the aerial tanker, in which case additional aerodynamic forces and moments acting on the receiver do emerge. The paper developed a mathematical model of aerodynamic characteristics of aircraft in jet vortex wake based on the set of aircraft flow-around calculation programs and wake flows. This technique can be used to model a flight in case one aircraft inadvertently enters the other aircraft's wake.

Gaitonde, D. V.

"MEAN FLOWFIELD STRUCTURE OF A SUPERSONIC THREE-DIMENSIONAL BASE FLOW"

Journal of Aircraft, Vol. 47, No. 2, March-April 2010, pp. 368-382.

The mean flow field structure in the wake region of a circular cylinder at a 10 deg angle of attack in a Mach 2.5 flow is described. Results from the full three-dimensional Reynolds-averaged Navier-Stokes equations, supplemented with a compressibility-corrected two-equation turbulence model, are compared with extensive available experimental data. Mesh resolved results indicate that surface pressure trends on both the afterbody and the base are reproduced well, but quantitative differences of about 15 percent are observed in different regions. The main experimental observations of the shock pattern, surface oil flow on the afterbody and the base surfaces, velocity vector plots in the symmetry and lateral planes, and end-view flow images are reproduced to good accuracy. Based on this success, the computed solution is employed to generate a model for the mean flow. The main feature is a pair of longitudinal vortices separated by high-speed fluid entrained primarily from the leeward and lateral afterbody boundary layers and bounded from below by the windward afterbody layer. The mean vorticity distribution reveals a vortex core pair forming a horseshoe-like structure. The three-dimensional wave structure is elucidated and correlated with the streamline pattern.

Galbraith, R., Coton, F. and Green, R.

"DETAIL OF MAIN/TAIL-ROTOR VORTEX INTERACTION ON ROTORCRAFT"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

The paper describes the work carried out at Glasgow University on orthogonal interaction of a rotor-tip vortex with a fixed blade mimicking the tail rotor. The vortex is generated from a single bladed rotor mounted in the contraction of the Glasgow Argyle wind tunnel. The pitch of the blade was varied using

a smooth cam such that it is pitched up as the blade approached the tunnel working section and pitched down as it departed. This resulted in a sequence of near orthogonal vortices travelling down the working section. They were true trailing vortices containing the associated axial flow component. The fixed blade was mounted offset to the center of the wind tunnel and was liberally instrumented with pressure transducers. The blade could be adjusted both vertically and in pitch. It is clear from the data that for the airfoil surface, on which the axial flow of the vortex is towards the airfoil, there is a pressure pulse resulting in a compression which, as the vortex convects across the chord, disappears and a suction wave develops. On the opposite side, where the axial flow is away from the airfoil, there is increased suction that is observed throughout the convective process. When these interactions were observed using particle image velocimetry, and the velocity vectors decomposed into the radial and tangential components, the immediate interaction appears to be the combination of a simple vortex and a source. The source being positive on the compression side and negative on the suction side. To assess how appropriate the aerodynamic modelling in the wind tunnel has been, the presentation will finally discuss the replacement of the fixed blade by an instrumented tail-rotor. That rotor will have fewer transducers and hence less fidelity. Nonetheless, similar temporal pressure data, from both the fixed and the rotating rotor, will indicate appropriate modelling of the interaction.

Gallacher, D. and More, G.

"LIDAR MEASUREMENTS AND VISUALISATION OF TURBULENCE AND WAKE DECAY LENGTH"

EWEA 2014 Annual Conference, Poster PO 175, March 2014, Barcelona, Spain.

Galion Lidar was used to measure the wake of a wind turbine to investigate wake decay length. The PARK wake model using a wake decay constant of 0.038 was compared with the measured data to assess its effectiveness for wake modelling. The data was filtered to periods where there was a single wake only. It was found that the PARK wake model generally predicts the recovery (i.e. over predicts wake loss) towards free stream inflow wind speed as measured by the Lidar at low wind speeds with better agreement in the high inflow wind speed bins. The PARK wake model shows best agreement with the Lidar data at high inflow wind speed and proves a good match for the 16-18 m/s inflow wind speed. In the 5 to 14 rotor diameter downstream distance PARK is seen to over predict wake losses across wind speed bins. After this distance the comparison with the Lidar data is less consistent and a wake scan with a longer focus point to capture this area in more detail would shed more light on the comparison between the model and the data.

Gallaire, F. and Chomaz, J.-M.

"THREE-DIMENSIONAL INSTABILITY OF ISOLATED VORTICES"

Physics of Fluids, Vol. 15, No. 8, August 2003, pp. 2113-2126

We study the three-dimensional stability of the family of vortices introduced by Carton and McWilliams describing isolated vortices. For these vortices, the circulation vanishes outside their core over a distance depending on a single parameter, the steepness a . We proceed to the direct numerical

simulation of the linear impulse response to obtain both temporal and spatio-temporal instability results. In the temporal instability framework, growth rates are calculated as a function of the axial wavenumber k and the azimuthal wavenumber m . The stability analysis is performed at a Reynolds number of $Re=667$. It is shown that the most unstable mode is the axisymmetric mode $m = 0$, regardless of the steepness parameter in the investigated range. When the steepness a is increased the band of unstable azimuthal modes widens, i.e., larger m modes are destabilized. The study of the spatio-temporal spreading of the wave packet shows that the $m = 2$ mode is always the fastest traveling mode, for all studied values of the steepness parameter.

Gallaire, F. and Chomaz, J.-M.

"INSTABILITY MECHANISMS IN SWIRLING FLOWS"

Physics of Fluids, Vol. 15, No. 9, September 2003, pp. 2622-2639

We investigate the stability of the screened Rankine vortex with added plug flow where the azimuthal velocity decreases abruptly outside the core of the vortex. The jump in circulation is known to induce centrifugal and azimuthal Kelvin-Helmholtz instabilities. Their effect on the stability of the different azimuthal wave number m is discussed using physical considerations associated with asymptotic expansions and numerical computations of the dispersion relation. It is shown that the axial shear and centrifugal instability are active for all m , and that modes with m greater than or equal to 2 are also destabilized by azimuthal shear. In contrast, the bending modes $m = \text{plus/minus } 1$ are stabilized by a coupling with Kelvin waves in the core. Effects of rotation on the absolute/convective transition are also discussed. The absolute instability of positive helical modes is seen to be promoted by centrifugal instability and azimuthal shear.

Gallaire, F., Rott, S. and Chomaz, J.-M.

"EXPERIMENTAL STUDY OF A FREE AND FORCED SWIRLING JET"

Physics of Fluids, Vol. 16, No. 8, August 2004, pp. 2907-2917

The present study concerns the response of a swirling jet to various azimuthal modes and frequencies forced at the nozzle exit. The different unforced dynamical states are first described as a function of the swirl setting, determined from measured velocity fields in the longitudinal plane using particle image velocimetry. A second experimental technique, based on laser induced fluorescence, is described, which is more suited to the description of the low-amplitude response of the jet to the forcing. It is shown that the receptivity of the jet is very poor when the forcing is set to the naturally prevailing azimuthal mode ($m = 2$) and frequency. In contrast, a strong response is observed for both co-rotating and counter-rotating forced azimuthal modes ($m = \text{plus/minus } 2$, $m = \text{plus/minus } 3$) for frequencies about one order of magnitude larger than the frequency prevailing in the absence of forcing. Finally, the present actuator is seen to be ineffective in preventing the appearance of vortex breakdown itself.

Gallaire, F., Ruith, M., Meiburg, E., Chomaz, J.-M. and Huerre, P.

"SPIRAL VORTEX BREAKDOWN AS A GLOBAL MODE"

J. Fluid Mech., Vol. 549, 2006, pp. 71-80

The spiral form of vortex breakdown observed in the numerical simulations of Ruith et al. (J. Fluid Mech., vol. 486, 2003, p. 331) is interpreted as a nonlinear global mode originating at the convective/absolute instability transition point in the lee of the vortex breakdown bubble. The local absolute frequency at the transition station is shown to yield a satisfactory prediction of the precession frequency measured in the three-dimensional direct numerical simulations.

Gallman, J. M., Schultz, K.-J., Spiegel, P. and Burley, C. L.

"EFFECT OF WAKE STRUCTURE ON BLADE-VORTEX INTERACTION PHENOMENA: ACOUSTIC PREDICTION AND VALIDATION"

Journal of Aircraft, Vol. 35, No. 2, March-April 1998, pp. 267-273.

The higher harmonic control aeroacoustic rotor test conducted at Duits-Nederlandse Wind Tunnel has made extensive measurements of the rotor aerodynamics, far-field acoustics, wake geometry, and the blade motion for powered descent flight conditions. These measurements have been used to validate and improve the prediction of blade-vortex interaction (BVI) noise. The improvements made to the BVI modeling after the evaluation of the test data are discussed. The effect of these improvements on the acoustic-pressure predictions is shown. These improvements include restructuring the wake, modifying the core size, incorporating the measured blade motion into the calculations, and attempting to improve the dynamic blade response. A comparison of four different implementations of the Ffowcs Williams and Hawkings equation is presented. A common set of aerodynamic input has been used for this comparison.

Gallman, J. M., Tung, C. and Low, S. L.

"THE EFFECTS OF VORTEX MODELING ON BLADE-VORTEX INTERACTION NOISE PREDICTION"

AIAA Paper No. 1995-0832, January 1995, Reno, NV.

The use of a blade vortex interaction noise prediction scheme, based on CAMRAD/JA, FPR and RAPP, quantifies the effects of errors and assumptions in the modeling of the helicopter's shed vortex on the acoustic predictions. CAMRAD/JA computes the wake geometry and inflow angles that are used in FPR to solve for the aerodynamic surface pressures. RAPP uses these surface pressures to predict the acoustic pressure. Both CAMRAD/JA and FPR utilizes the Biot-Savart Law to determine the influence of the vortical velocities on the blade loading and both codes use an algebraic vortex model for the solid body rotation of the vortex core. Large changes in the specification of the vortex core size do not change the in-plane wake geometry calculated by CAMRAD/JA and only slightly affect the out-of-plane wake geometry. However, the aerodynamic surface pressure calculated by FPR changes in both magnitude and character with small changes to the core size used by the FPR calculations. This in turn

affects the acoustic predictions. Shifting the CAMRAD/JA wake geometry away from the rotor plane by 1/4 chord produces drastic changes in the acoustic predictions indicating that the prediction of acoustic pressure is extremely sensitive to the miss distance between the vortex and the blade and that this distance must be calculated as accurately as possible for acceptable noise predictions. The inclusion or exclusion of a vortex in the FPR-RAPP calculation allows for the determination of the relative importance of that vortex as a BVI noise source. Being able to identify which vortex is responsible for the largest noise sources will lead to improved BVI noise reduction methods.

Gallman, J. M., Tung, C., Schultz, K.-J., Splettstoesser, W., Buchholz, H., Spiegel, P., Burley, C. L., Brooks, T. F. and Boyd Jr., D. D.

"EFFECT OF WAKE STRUCTURE ON BLADE-VORTEX INTERACTION PHENOMENA: ACOUSTIC PREDICTION AND VALIDATION"

AIAA Paper 1995-0022, June 1995, Munich, Germany.

During the Higher Harmonic Control Aeroacoustic Rotor Test, extensive measurements of the rotor aerodynamics, the far-field acoustics, the wake geometry, and the blade motion for powered, descent, flight conditions were made. These measurements have been used to validate and improve the prediction of blade-vortex interaction (BVI) noise. The improvements made to the BVI modeling after the evaluation of the test data are discussed. The effects of these improvements on the acoustic-pressure predictions are shown. These improvements include re-structuring the wake, modifying the core size, incorporating the measured blade motion into the calculations and attempting to improve the dynamic blade response. A comparison of four different implementations of the Ffowcs Williams and Hawkings equation is presented. A common set of aerodynamic input has been used for this comparison.

Gallo, W.

"WAKE TURBULENCE LITIGATION"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 48-1 - 48-7

All of the published wake-turbulence-encounter legal decisions have been analyzed and summarized to present a picture of the bottom line effect of the wake turbulence dangers. Eighteen such cases, which at least have alleged wake turbulence as the cause of an airplane crash, are listed and a brief set of circumstances or particulars are included to show a brief history of such litigation. Obviously, the mere allegation, as found in a lawsuit, brought by some lawyer, does not always translate into an actual wake turbulence encounter. Some courts have decided, that despite allegations and testimony by a so-called expert in the field, the subject accident although alleged to be a wake turbulence accident was not attributable to wake turbulence at all.

Gally, T.

"AERODYNAMIC EVALUATION OF WING TIP MOUNTED NACELLES"

AIAA Paper 2001-2482, Anaheim, CA, June 2001

A computational investigation of the impact of wing tip mounted engine nacelles was undertaken in order to quantify potential improvements in performance and reductions in wake vortex strengths as had been identified in previous wind tunnel tests by Patterson, et al. The results obtained indicated that the bulk of the performance gains are associated with the diameter of the wing tip body and not with the presence of axial flow in the tip vortex core. However, the tip vortex strength is reduced by such core flow and forced core blowing does enhance the viscous dissipation of the vortex. The possibility still exists to affect the tip vortex stability through blowing, but vortex breakdown was not observed in the computational analysis.

Galovic, B., Grozdanic, B. and Steiner, S.

"INFLUENCE OF WAKE-VORTEX TURBULENCE ON THE FLIGHT SAFETY"

Promet Traffic, Vol. 9, No. 1-2, 1997, pp. 1-14

With the growing air traffic intensity, at some airports we are more often faced with the fact that aircraft land or takeoff one after another. Since every aircraft leaves a turbulent vortex behind, which acts unexpectedly and is destabilizing for the aircraft flying into it, the flight safety for such repeated landings and takeoffs becomes questionable. Determining the minimum safety time interval between the repeated operations becomes imperative and a limiting factor for some airports with high traffic intensity. Unlike military flying, where crew is trained to fly in a group, in civil air traffic the crew is not trained for such flying and on top of it mostly operate on large aircraft, which produce very strong turbulent vortex. Additional sophisticated equipment in new modern aircraft improves navigation, communication and steering of the aircraft, but does not insure it from flying into an invisible turbulent vortex. This paper discusses the vortex generation, its nature and factors that influence its intensity and duration. The paper also deals with a model of calculating the probability of flying into a turbulent vortex regarding time interval of repeated operations, and influence of sophisticated equipment installed, on the stability and flight safety of an aircraft. Conclusion underlines the need to standardize the minimum safety time interval separation between the repeated operations, with the aim of improving flight safety.

Galpin, D., Pugh, C., Cobo, D. and Vinagre, L.

"EUROPEAN WAKE VORTEX MITIGATION BENEFITS STUDY WORK PACKAGE 3 DELIVERABLE: HIGH LEVEL BENEFITS ANALYSIS AND SYSTEMIC ANALYSIS"

TRSD03/WP3, 2005, Eurocontrol.

PART A: This technical contribution to Work Package 3 consists of a high-level benefits study conducted for the airports brought forward from Work Package 1. Benefits (in terms of extra

movements) were estimated for 3 concepts - ATC-Wake, CREDOS, and Time-Based Spacing - and took advantage of the meteorological profiles produced in Work Package 2. PART B: This technical contribution to Work Package 3 consists of a high-level systems analysis describing the required modifications for the implementation of the WV mitigation concepts considered in this study on a generic ATM system. This analysis intends to serve as an input to develop the costs assessment required to obtain the Cost Benefit Analysis for the different target airports identified in Work Package 1.

Gan, L. and Nickels, T. B.

"AN EXPERIMENTAL STUDY OF TURBULENT VORTEX RINGS DURING THEIR EARLY DEVELOPMENT"

Journal of Fluid Mechanics, Vol. 649, 2010, pp. 467-496.

In this paper, the early development of turbulent vortex rings at two Reynolds numbers is studied using two-dimensional and stereoscopic particle image velocimetry (PIV). In the late 1980s, a similarity theory of turbulent vortex rings was proposed and this theory was tested primarily using Doppler velocimetry. However, because of limitations of the experimental technique, the tests were inconclusive and important assumptions could not be checked. Because single-point measurements were used, vortex ring structures could only be inferred using a complex signal analysis technique. In this study, the PIV technique provides spatial measurements of the full field of the cross-section of a ring from which a more rigorous investigation of the similarity theory is possible. Because the region over which the similarity theory appears to hold starts at about 2.5 orifice diameters downstream, this study focusses on the early development region from this point to 8 diameters downstream. Finally, Reynolds stresses and turbulence production contours are presented. The effects of ring dispersion on the measurements is also studied and quantified.

Gan, L., Dawson, J. R. and Nickels, T. B.

"ON THE DRAG OF TURBULENT VORTEX RINGS"

Journal of Fluid Mechanics, Vol. 709, 2012, pp. 85-105.

In this paper the pressure field during the early development of turbulent vortex rings at two Reynolds numbers is determined using temporally resolved two-dimensional and stereoscopic particle image velocimetry. The pressure gradient terms are obtained by solving the incompressible Euler equation so that the drag coefficients of the vortex rings can be evaluated. Maxworthy and Glezer and Coles each developed models to describe the long-term physics of turbulent vortex rings: the former developed a semi-empirical model which permits loss of impulse via the shedding of vorticity into the wake whereas the latter developed a similarity model based on invariance of the hydrodynamic impulse. Maxworthy's model implies that a significant correction to the similarity solution is required to account for the drag on the vortex ring bubble. We show that during the early development of the turbulent vortex rings the drag is very small and the similarity scaling can basically be retained.

Gan, L., Nickels, T. B. and Dawson, J. R.

"AN EXPERIMENTAL STUDY OF A TURBULENT VORTEX RING: A THREE-DIMENSIONAL REPRESENTATION"

Experimental Fluids, Vol. 51, 2011, pp. 1493-1507.

This paper presents a reconstruction of the three-dimensional velocity field of a turbulent vortex ring by means of Taylor's hypothesis. Stereoscopic PIV is used to acquire three velocity component information on a plane. The accuracy of the Taylor's hypothesis for this particular flow pattern is first discussed, and the three-dimensional velocity and vorticity information are then presented. This study also introduces an azimuthally averaging method to give a mean structure in cylindrical coordinates from a single realization and from which turbulent stresses and production can be estimated. The azimuthally averaged quantities are then compared with the ensemble-averaged results from the previous planar (two-dimensional and stereoscopic) PIV experiments.

Ganci, G., Altman, A. and Rodewald, J.

"IDENTIFICATION OF AIRCRAFT BY THEIR UNIQUE TURBULENT WAKE SIGNATURE: EXPERIMENTAL VALIDATION"

AIAA Paper No. 2012-0066, January 2012, Nashville, Tennessee.

Earlier work on the theoretical foundation for the identification of aircraft by their unique turbulent wake signature is experimentally validated. A brief review of this theoretical foundation will be discussed wherein the drag coefficient can be used to estimate either a Reynolds Stress distribution or (indirectly) a model of the velocity profile of the turbulent wake. A previously unpublished sensitivity study on the conditions of application of the method is included. This sensitivity reviews the robustness of the method to differentiate between aircraft across a much wider range of cruise and payload conditions than those previously published as well as a few corners where the method could potentially have difficulty differentiating between aircraft. Experimentally, initially the Reynolds stress distribution downstream of a circular cylinder is determined using Particle Image Velocimetry (PIV) in the University of Dayton low speed wind tunnel and those results compared to the predicted Reynolds Stress distribution calculated from the drag coefficient obtained through direct force measurement. Subsequently, the Reynolds stress distribution downstream of a moderate aspect ratio wing obtained through PIV is similarly compared to a predicted Reynolds Stress distribution derived through the drag coefficient obtained from direct force measurement. Finally, a small remote-control twin engine aircraft is tested with wind-milling propellers and its drag measured from a force balance is used to generate the expected Reynolds stress distribution. This distribution is then compared to the Reynolds stress distribution obtained from PIV downstream of the model where the wake had not yet achieved a self-preserved state. This prevented a complete demonstration of practical feasibility of the technique; however, several key underlying assumptions of the method are validated.

Gand, F.

"ZONAL DETACHED EDDY SIMULATION OF A CIVIL AIRCRAFT WITH A DEFLECTED SPOILER"

AIAA Journal, Vol. 51, No. 3, March 2013, pp. 697-706.

This paper presents the simulation of a wing/body configuration with a deflected spoiler using the Zonal Detached Eddy Simulation approach in an emergency dive scenario at the Reynolds number based on the wing chord $Re=5,000,000$. The objective is to assess the reliability of this numerical method in the framework of the creation of aerodynamic data models in off-design conditions. The mesh is built using the Chimera technique (or overset grids) to gather multiblock, structured, near-wall grids and Cartesian off-body grids. The results are compared to wind tunnel data and show the dramatic increase of accuracy provided by the zonal detached eddy simulation approach in the spoiler area compared to a standard steady Reynolds-averaged Navier-Stokes simulation using the Spalart-Allmaras model. Furthermore, the zonal detached eddy simulation gives insights on the unsteady properties of the turbulent structures downstream of the spoiler, which is of major importance in the aerodynamic design process of an aircraft related to tail buffet.

Gandhi, N. T.

"AUTOMATIC DEPENDENT SURVEILLANCE-BROADCAST ENABLED, WAKE VORTEX MITIGATION USING COCKPIT DISPLAY"

MS Thesis, December 2012, Ohio University, Athens, OH.

Wake turbulence has the potential to cause accidents during the landing phase of flight. This thesis work documents the development and testing of a prototype cockpit display to help pilots avoid this wake turbulence using ADS-B technology. Several landing profiles of the wake generating aircraft and the trailing aircraft were created using computer simulations to generate the synthetic data. A tracking algorithm was developed to compute the altitude of the leading aircraft to be displayed in the altitude strip of the cockpit display. This algorithm will search for all the points of flight data of a leading aircraft, within a predefined region near a trailing aircraft. This flight data is projected on a primary or multifunction display to create an imaginary scenario and tested for data acquisition and transmission from one aircraft to another. The parameters and the number of bits that are necessary to transmit these data via the ADS-B for avoiding the wake turbulence, especially in the case of busy airports are documented. As a final step, necessary hardware was installed in two GA (General Aviation) aircraft and a flight test was performed. The flight-tested prototype successfully provided the pilot of the trailing aircraft with intuitive information on a multifunction display to avoid wake turbulence.

Ganesh, B. and Komerath, N.

"UNSTEADY AERODYNAMICS OF ROTORCRAFT IN GROUND EFFECT"

AIAA Paper 2004-2431, June 2004, Portland, OR.

The aerodynamic characteristics of rotorcraft flight close to the ground are studied. Flow visualization was done to identify the flow structure in ground effect, and compare it with the out of ground effect flow structure. Hotwire measurements were done to quantify time scales of fluctuations. Six

component force measurements were done to measure the loads at various advance ratios and yaw angles.

Gangwani, S. T.

"DETERMINATION OF ROTOR WAKE INDUCED EMPENNAGE AIRLOADS"

American Helicopter Society Northeast Region National Specialists' Meeting on Helicopter Vibration Technology for the Jet Smooth Ride, November 1981, Hartford, CT.

An efficient time-domain method has been developed to determine the unsteady vibratory air-loads produced by the interaction of the main rotor wake with the helicopter empennage. An analysis technique has been followed wherein a rotor wake program is used to determine the main rotor wake position and the strength of blade tip vortices that are located near the empennage surfaces. A nonlinear lifting surface analysis is utilized to predict the aerodynamic loads on the empennage surfaces in the presence of these concentrated vortices. This nonlinear analysis has been formulated so as to include pertinent effects such as the suction effects of the interacting vortices and the effects of shed vorticity behind the empennage surfaces. The problem is solved in a stepwise manner (time-domain); that is, a period corresponding to one blade passage is divided into many time intervals and unsteady air-loads are computed at each step. The output of the analysis consists of chordwise and spanwise air-load distributions on the empennage surfaces at each time step. These air-load distributions are converted into the harmonic air-loads that are applied to the tail boom of the helicopter for use in vibration analysis. The results of a limited correlation study involving the application of the present computer analysis to a full-scale helicopter stabilizer indicate a reasonably good correlation between analytical predictions and the flight test data.

Ganzevles, F. L. A., deBruin, A. C. and Puffert-Meissner, W.

"A QUANTITATIVE ANALYSIS OF VISCOUS AND LIFT-INDUCED DRAG COMPONENTS FROM DETAILED WAKE MEASUREMENTS BEHIND A HALF-SPAN MODEL"

NLR-TP-2002-320, June 2000, National Aerospace Laboratory, Cambridge, UK

In the Low-Speed Wind Tunnel of DNW detailed wake surveys were made behind an aircraft half-span model (ALVAST) using a rake with 5-hole probes. Different model configurations were considered including a body with wing, a body with wing and a Through Flow Nacelle and a body with wing and a low-powered Counter Rotating Ultra-high-bypass Fan. The lift and drag coefficients calculated from the measured velocities and pressures in the wake are compared with the force coefficients measured with a force balance. The spanwise distributions of lift, viscous drag and induced drag are presented.

Gao, H. and Agrwal, R. K.

"NUMERICAL STUDY OF A HOVERING HELICOPTER ROTOR BLADE IN GROUND EFFECT"

AIAA Paper 2019-1099, January 2019, San Diego, CA.

This paper focuses on the numerical simulation of a 3-D hovering helicopter rotor blade in ground effect in transonic regime. The study consists of two parts. The first part involves the study of blade pressure distribution, lift on blade sections and rotor thrust performance. Along the span wise direction near the blade tip, local Mach number becomes close to 1 and shock is captured numerically. The numerical results are validated against the experimental data for the hovering rotor blade. When rotor blade is close to the ground, the change in blade pressure distribution is studied. The second part involves mainly the properties of the wake when rotor blade is close to the ground. It includes the trajectory and strength of the wake.

Gao, H., Li, J., Chan, P. W., Hon, K. K. and Wang, X.

"PARAMETER-RETRIEVAL OF DRY-AIR WAKE VORTICES WITH A SCANNING DOPPLER LIDAR"

Optics Express, Vol. 28, No. 13, June 2018, pp. 16377-16392.

A wake vortex is a form of irregular airflow generated by a flying aircraft, which can cause a severe hazard for aviation. To quantify the hazard of a wake after fully roll-up and before rebound, this paper proposes an algorithm to retrieve its characteristic parameters (circulation, vortex-core positions, and vortex-core radii) with a scanning Doppler Lidar. In the algorithm, a governing equation related to the Doppler velocities and characteristic parameters is established based on the aerosols' weak inertia, from which the target parameters are solved with an optimization method. During the process, the distortion of Doppler velocity caused by the scanning of the Lidar beam is adjusted by the Doppler acceleration to achieve better estimations of the target characteristic parameters. Good performance of the algorithm has been verified by simulation and field detection data.

Garbeff II, T. J., Huthmacher, R., Tso, J., Martin, P. B. and Tung, C.

"AN EXPERIMENTAL SURVEY OF A WING-TIP VORTEX IN A CONTRACTED FLOW"

AIAA Paper No. 2010-4616, June 2010, Chicago, Illinois.

Vortex stretching is a phenomenon vital to many areas of aerodynamic study. Circumstances arise where the dynamics of evolving vortices can significantly influence surrounding flow fields. Some of these circumstances include wing tip vortex persistence related to formation flight, the dynamics of leading-edge vortices in delta wing flight, vortex interactions with buildings, and complex rotorcraft wake flow fields. In these cases, vortex interaction can have beneficial or detrimental effects. The evolution of wing-tip vortices in wake flow fields has been well studied through experiment. Typically, the major concern of these studies involved the viscous decay of wing-tip vortices with applications to close-proximity flight. This experiment sought to detail the evolution of a wing-tip vortex shed into a favorable pressure gradient. Cross sectional velocities were measured at sequential locations in a mild contraction in the Cal Poly 3 x 4 ft low-speed wind tunnel to examine the circumferential velocity and vorticity evolutions of the vortex in the streamwise direction. Afterwards, these experimental results

were compared with previous experiments as well as an approximate analytical solution to a vortex in stretched flow.

Garcia, A. J. and Barakos, G. N.

"ACCURATE PREDICTIONS OF ROTOR HOVER PERFORMANCE AT LOW AND HIGH DISC LOADINGS"

Journal of Aircraft, Vol. 55, No. 1, January-February 2018, pp. 89-110.

This paper presents evidence on the ability of modern computational fluid dynamics methods to accurately predict hover performance of rotors with modest computer resources. The paper uses two well-studied blades, the S-76 main rotor blade and the XV-15 tiltrotor blade. The results are compared with experiments and show that the performance is well predicted. In addition, the employed computational fluid dynamics method was able to capture the effects of the tip Mach number, tip shape, blade aeroelasticity, and flow transition on the performance of the blade as well as on the wake structure and the rotor acoustics.

Garcia, A. J. and Barakos, G. N.

"NUMERICAL SIMULATIONS ON THE ERICA TILTROTOR"

Aerospace Science and Technology, Vol. 64, May 2017, pp. 171-191.

This paper presents aerodynamic calculations of the model-scale ERICA tiltrotor with high-fidelity computational fluid dynamics. The aim of this work is to assess the capability of the present CFD method in predicting air-loads on the tiltrotor at different flight configurations. In this regard, three representative flight configurations of the ERICA were selected, corresponding to airplane, transition corridor, and helicopter modes, covering most modes of tiltrotor flight. The rotor blades were fully resolved and the use of a uniform and non-uniform actuator disk was also put forward to quantify the effect of the rotor on the fuselage loads. A fundamental investigation of the effect of the aerodynamic interference between the rotor and wing of the tiltwing aircraft is also shown. The employed CFD method was able to capture the aerodynamics of the different configurations and the overall agreement obtained with the experimental data demonstrates the capability of the present CFD method in accurately predict tiltrotor flows.

Garcia, C. M., Jackson, P. R. and Garcia, M. H.

"CONFIDENCE INTERVALS IN THE DETERMINATION OF TURBULENCE PARAMETERS"

Experiments in Fluids, Vol. 40, 2006, pp. 514-522.

This paper quantifies uncertainty in turbulence parameters using the moving block bootstrap technique (MBB). This technique provides a good approximation of confidence intervals of turbulence parameters such as time and length scales of turbulent flow, convective velocities and dissipation of turbulent kinetic energy which cannot be estimated based on the available standard methodology

because of their computational complexity and reliance on correlation structure in the signal. The validation consisted of a comparison between uncertainty estimates of various parameters from MBB and those from analytical and experimental data.

Garcia, D. L. and Katz, J.

"TRAPPED-VORTEX IN GROUND EFFECT"

AIAA Paper No. 2002-3307, St. Louis, MO, June 2002

The effects of vortices trapped between a flat plate and a ground plane were studied in a wind tunnel experiment. The flat plate was mounted parallel to the ground to represent the lower surface of a generic road vehicle. Rectangular vortex generators mounted onto the plate were used to generate streamwise vortices between the plate and the ground plane. The main variables investigated were the ground clearance and vortex generator orientation, both influencing the trapped vortex strength. The experimental data indicates that considerable aerodynamic loads can be created with such vortex generators, particularly for small ground clearance values (even at zero plate incidence).

Gardner, A. D., Wolf, C. C. and Raffel, M.

"REVIEW OF MEASUREMENT TECHNIQUES FOR UNSTEADY HELICOPTER ROTOR FLOWS"

Progress in Aerospace Sciences, Vol. 111, 2019, pp. 100566-1 - 100566-17.

Garg, A. K. and Leibovich, S.

"SPECTRAL CHARACTERISTICS OF VORTEX BREAKDOWN FLOWFIELDS"

Phys. Fluids, Vol. 22, No. 11, November 1979, pp. 2053-2064

Laser-Doppler anemometer measurements upstream and in the wakes of vortex breakdowns of bubble and spiral types are described. Spectral analysis of the data indicates prominent oscillations in the wakes at less than 10 Hz. These oscillations correspond closely to theoretical predictions of the linearly most unstable normal modes of the time-averaged mean flow profiles. The oscillations are more energetic, and vortex core expansions are greater for flows with a bubble form of vortex breakdown, which is therefore regarded as the stronger form of breakdown.

Garmann, D. J. and Visbal, M. R.

"TRANSIENT ENCOUNTERS OF A NACA0012 WING WITH A STREAMWISE-ORIENTED VORTEX"

AIAA Paper 2015-3073, June 2015, Dallas, TX.

A high-fidelity numerical study has been conducted to examine the unsteady interactions resulting from a finite wing maneuvering into a streamwise-oriented vortex as a representative problem of wake encounters. A NACA0012 wing at an angle of 4 degrees and operating at a Reynolds number of $Re = 200000$ is dynamically maneuvered into the path of a stationary vortex, and the transient encounter is analyzed for three side-slip velocities corresponding to 10, 20, and 40 percent of the free stream. The wing is shown to traverse a range of flow regimes, including instances of vortex pairing of the tip and incident vortices that lead to mutual induction and attenuation of the pair, tip vortex suppression as the impingement passes inboard of the wingtip, and induced separation that precipitates an abrupt transition at the leading edge. The overall flow structure is mostly consistent among the wing speeds examined, indicating an almost quasi-stationary response with relative vortex position. However, a notable lag is observed in the development of a spiraling instability in the incident vortex just upstream of the wing. With slower encounter speeds, the vortex core exhibits a pronounced spiraling undulation that persists farther upstream earlier in the motion. The advanced development is attributed to prolonged exposure to the adverse pressure gradient from stagnation on the underside of the wing that decelerates the core axial flow below known stability bounds of the vortex. Additionally, a dynamic loading effect is identified prior to the vortex crossing inboard of the wingtip, whereby the incident structure's relative position at peak loading shifts outboard with increased wing speed. The peak magnitudes of lift, pitching moment, and rolling moment coefficients are also shown to scale proportionally with the wing's side-slip speed as they are predicated upon an enhanced tip vortex development. In all cases as the wing approaches the vortex, an upstream progression of separation, transition, and reattachment over the leading-edge leads, which forward tilts the force vector and reduces the drag. Once the vortex is brought inboard, however, the drag saturates, and the other quantities exhibit a nearly quasi-stationary response with vortex position as the wingtip unloads.

Garmann, D. J. and Visbal, M. R.

"INVESTIGATION OF THE UNSTEADY TIP VORTEX STRUCTURE ON A NACA0012 WING AT FIXED INCIDENCE"

AIAA Paper 2017-1002, January 2017, Grapevine, TX.

High-fidelity implicit large-eddy simulation is used to investigate the dynamics of wingtip vortices formed on an aspect-ratio-four NACA0012, rounded-tip wing at $Re = 200,000$ for incidence of α greater than or equal to 4 and less than or equal to 16. At its initial separation and inception, the tip vortex core exhibits a strengthening favorable pressure gradient with increased angle of attack that promotes acceleration of its axial flow to values higher than the free-stream speed for α greater than or equal to 8 degrees, or jet-like vortices. Approaching the trailing edge, however, the core is subjected to an adverse pressure gradient that decelerates the core flow before entering the wake. The extent and strength of this adverse region grows with increased incidence, but it does not reach a sufficient level to stagnate the core flow and cause breakdown for the conditions examined. The nature of the vortex (wake- or jet-like) is determined through this pressure gradient above the wing and does not appear to be associated with wake interactions. Analysis of the instantaneous and time-mean flow also reveals the formation, separation, and entrainment of shear-layer substructures within the tip vortex feeding sheet are stationary features, i.e. fixed in space and time. Interactions with the wake,

however, are highly unsteady as wake vortices shed from the wing's trailing edge are entrained into the vortex periphery.

Garmann, D. J. and Visbal, M. R.

"FURTHER INVESTIGATIONS OF THE TIP VORTEX ON AN OSCILLATING NACA0012 WING"

AIAA Paper 2016-4343, June 2016, Washington, DC.

The unsteady character of the wingtip vortex formed on a low-amplitude/high-frequency heaving wing is examined using high-fidelity numerical simulation. The wing of aspect ratio $AR = 6$ has a NACA0012 airfoil section and a rounded tip, and it operates at a Reynolds number of $Re = 200,000$, free-stream Mach number of 0.1, and fixed incidence of 8 degrees. Three plunging motions are considered with amplitudes of $A/c = 0.02$ or 0.03 and reduced frequencies of $k = (\pi)fc/U = 1.05$ or 2.00 . The chosen kinematics provide cases of mild, moderate, and extreme excursions in effective angle of attack that induce significant unsteadiness in the tip vortex but also avoid wing stall. The overall flow structure is characterized by a similar separation, transition, and reattachment process, albeit with varying levels of intensity and time scales. The tip vortex formation is distinguished by an initially laminar feeding sheet that separates from the underside of the wingtip and reattaches on the upper surface. As it continues to roll up towards the tip, a secondary separation ensues at advanced chordwise stations. As the wing plunges downward, this separation progresses forward towards the leading edge, which also leads to the inception of spiraling sub-structures in the feeding sheet that are entrained into the tip vortex periphery and are stretched longitudinally. Higher frequency and amplitude promote a more compact tip vortex core as the structure separates from a more upstream position. The location of separation balanced with the variation in adverse streamwise pressure gradient magnified within the tip vortex core, precipitate alternating moments of axial velocity wake- and jet-like profiles that persist well into the near-wake, where axial velocity fluctuations on the order of 60 percent of the free-stream speed are observed. Additionally, the near-field evolution of the tip vortex is augmented by a motion-induced wandering that becomes increasingly pronounced with more aggressive kinematics. Significant and growing vertical excursion are found with downstream location that far exceeded the initial offsets of the imposed wing motion. All cases develop spanwise excursions in the vortex trajectory leading to an induced orbital motion. The higher frequencies and amplitudes also promote dramatic tilting of the trajectory relative to its initial vertical motion. This unintended wandering may have serious implications for reliable vortex tracking based on wing position alone.

Garmann, D. J. and Visbal, M. R.

"ANALYSIS OF TIP VORTEX NEAR-WAKE EVOLUTION FOR STATIONARY AND OSCILLATING WINGS"

AIAA Journal, Vol. 55, No. 8, August 2017, pp. 2686-2702.

A numerical study is conducted to characterize the tip vortex unsteady evolution on a rounded-tip NACA0012 wing of aspect ratio $AR = 6$ operating at a Reynolds number of $Re = 200,000$ and an incidence of 8 deg. Stationary and plunging wing configurations are examined as representative

problems of aircraft wandering, wing vibration, or structural compliance that may all drastically affect the nature of the tip vortex and have important consequences in applications of formation flight, for instance. The high-frequency ($k = 2.09$), low-amplitude ($A = \pm 0.02c$) heaving motion of the wing promotes significant three-dimensionality of the overall flow structure with substantial variations in the tip vortex structure, including shear-layer substructure formation through enhanced separation and stretching, and alternating wake-like and jet-like behavior of its axial flow that leads to transitory enlargement or contraction of its core. The initial low-amplitude vertical displacement of the vortex grows dramatically as the structure advects into the wake, and a significant self-induced orbital motion results, which could be detrimental for downstream aerodynamic surfaces or for reliable vortex tracking in real-world applications. The dynamic state of the vortex as it leaves the wing is also shown to persist well into the wake.

Garmann, D. J. and Visbal, M. R.

"INTERACTIONS OF A TRAILING VORTEX WITH A DOWNSTREAM NACA0012 WING"

AIAA Paper 2017-3319, June 2017, Denver, CO.

A high-fidelity numerical study has been conducted to investigate the unsteady interactions of a trailing vortex impinging upon a downstream wing. Two NACA0012, rounded-tip wings of aspect ratio $AR = 4$ and Reynolds number $Re = 200,000$ are effectively simulated in tandem as a representative problem of formation flight or blade/vortex interactions. The unsteady velocity fluctuations and dynamic wandering of the lead wing's tip vortex are modeled and prescribed at the inflow of the subsequent follower wing simulations. The chosen model provides an extremely favorable match of the time-mean and turbulent nature of the vortex, while also supplying a simple mechanism for the unsteady characterization of tip vortices. The dynamic behavior of the modeled vortex as it convects and subsequently interacts with the downstream wing is also examined. This is in an effort to extend the findings of previous studies with analytically-defined incident vortices to more realistic and relevant conditions. Similar types of interactions are found here, including vortex-induced variations in effective angle of attack on the downstream wing that lead to upstream propagation of separation, transition, and reattachment inboard of impingement, and enhanced attached flow near the tip. The vortex evolves into a spiraling structure upstream of the wing that alternately deflects to the upper and lower surfaces. The buffeting behavior appears as a time-mean bifurcation of the incident structure with discrete vortices passing to either side of the wing. One distinguishing feature here, however, is that the incident vortex exhibits a definitive spiral-type breakdown preceding its impact on the wing, which differs slightly from the helical instability in lieu of flow reversal encountered in previous investigations. The predominant commonality of the flow topology with previous studies of various Reynolds numbers and with drastically different incident structures indicates the robust nature of these types of interactions, which is promising for future study. Vortex-induced upwash also led to a lift-to-drag ratio increase of 63% over the baseline wing alone, but the enhancement was also accompanied by more than twice the force and moment root-mean-squared fluctuations.

Garmann, D. J. and Visbal, M. R.

"UNSTEADY EVOLUTION OF THE TIP VORTEX ON A STATIONARY AND OSCILLATING NACA0012 WING"

AIAA Paper 2016-0328, January 2016, San Diego, CA.

A numerical study is conducted to characterize the unsteady evolution of a tip vortex formed on a NACA0012 wing with an aspect ratio of $AR = 6$ and rounded tip that is operating at a Reynolds number $Re = 200,000$ and incidence of 8° . Stationary and plunging wing configurations are examined as representative problems of aircraft wandering, wing vibration, or structural compliance that may all drastically affect the nature of the tip vortex and have important consequences in applications of formation flight, to name one example. The high-frequency ($k = 2.09$), low-amplitude ($A = \pm 0.02c$) heaving motion of the wing promotes significant three-dimensionality of the overall flow structure with substantial variations in the tip vortex structure, including shear layer substructure formation through enhanced separation and stretching, alternating wake- and jet-like behavior of its axial flow that leads to transitory enlargement or contraction of its core. The initial low-amplitude vertical displacement of the vortex grows dramatically as the structure advects into the wake, and a significant self-induced orbital motion also results, which could be detrimental for downstream aerodynamic surfaces or for reliable vortex tracking in real-world applications. The state of the vortex as it leaves the wing is also shown to persist well into the wake.

Garmann, D. J. and Visbal, M. R.

"INTERACTION OF A STREAMWISE-ORIENTED VORTEX WITH A WING"

AIAA Paper 2014-1282, January 2014, National Harbor, MD.

This work examines the interaction of a streamwise-oriented vortex impinging upon a wing for applications in formation flight. An analytically defined vortex superimposed on a free-stream is convected toward an aspect-ratio-six wing oriented at an angle of 4° and Reynolds number of $Re = 20,000$ in order to characterize the unsteady loading and induced vortex separation. Several spanwise positions of the vortex are analyzed and three distinct flow regions are found. When the vortex is positioned outboard of, but in close proximity to the wingtip, it pairs with the tip vortex to form a dipole that propels itself away from the plate due to its self-induced velocity and diffuses slowly. When the incoming vortex is aligned with the wingtip, the incident and tip vortex feeding sheets interact quite strongly and become entrained in the circulation of the opposite structure, which diminishes the coherence of both vortices into the wake. Finally, when the incident vortex is positioned inboard of the wingtip, the vortex bifurcates in the time-mean sense with portions convecting below and above the wing. The increased effective angle of attack inboard of impingement enhances the three-dimensional recirculation region created by the separated boundary layer off the leading edge which draws fluid from the incident vortex inboard and diminishes its impact on the outboard section of the wing. The slight but remaining downwash present outboard of impingement reduces the effective angle of attack in that region resulting in a small separation bubble on either side of the wing in the time-mean solution effectively unloading the tip outboard of impingement. All incident vortex positions provide substantial increases in the wing's lift-to-drag ratio; however, significant sustained

rolling moments also result. As the vortex is brought inboard, the rolling moment diminishes and eventually switches sign, indicating that small changes in vortex position can cause dramatic moment variations, which will require dynamic and responsive control systems.

Garmann, D. J. and Visbal, M. R.

"UNSTEADY INTERACTIONS OF A WANDERING STREAMWISE-ORIENTED VORTEX WITH A WING"

AIAA Paper 2014-2105, June 2014, Atlanta, GA.

The unsteady interaction of wandering streamwise-oriented vortex impinging upon a finite wing are examined using high-fidelity numerical simulation. The incident vortex is prescribed analytically upstream of an aspect-ratio-six wing and is defined with a sinusoidal variation in its spanwise position. Two wandering amplitudes are considered, $0.25c$ and $0.5c$, oscillating around a mean location measure $0.25c$ inboard of the wingtip at a normalized frequency of $f_c/(U \text{ sub infinity}) = 0.2$. The imposed lateral motion of the vortex spatially evolves as it approaches the wing by inclining relative to its initial horizontal trajectory and also diminishing in amplitude. Just ahead of the wing, both wandering amplitudes are reduced by 36 percent, and the horizontal trajectory inclined by nearly 38 and 53 degrees, respectively, for the initial wandering amplitudes of $0.5c$ and $0.25c$. This streamwise development of the incident vortex path has implications on the subsequent interaction with the wing, as the wing's streamwise position relative to the vortex self-induced motion dictates how the surface will be impacted. The vertical offset of the vortex core was also shown to drive an eventual pinch-off and alternating attachment to the upper and lower surfaces, which then evolved into a horseshoe-like structure before coalescing into a ring vortex and convecting into the wake. This contrasts with the pinch-off experienced by a stationary vortex impacting a wing, which is driven by a spiraling instability in the vortex core induced by the upstream influence of the wing that reorients the vortex ahead of the leading edge. The wandering vortices examined here exhibited no signs of the same spiraling undulation. This finding prevents conclusions about the flow structure engendered by a stationary vortex impingement from being generated in the more dynamic wandering vortex interaction. Despite the differing pinch-off mechanisms, the unsteady loading experienced by the wing is shown to fall within the bounds of the time-mean loading of the stationary impinging vortices.

Garner, H. C.

"THE EVALUATION OF DOWNWASH AT LARGE SPANWISE DISTANCES FROM A VORTEX LATTICE"

R&M 2808, Dec. 1950, Aeronautical Research Council, Great Britain

This note explains an improved numerical method of evaluating the contributions to the downwash at moderate or large spanwise distances from a vortex lattice. By allowing freedom of choice of the chordwise positions of the discrete vortices of the lattice, it is possible to select three definite chordwise positions and strengths of vortices at each of these positions dependent on the chordwise pressure distribution, so as to determine the downwash with good accuracy for three particular

pressure distributions proportional to $\cot(1/2 \theta)$, $\sin(\theta)$ and $\sin(2 \theta)$. The corresponding chordwise loading factors have also been evaluated for deflected flaps.

Garnet, M. and Altman, A.

"IDENTIFICATION OF ANY AIRCRAFT BY ITS UNIQUE TURBULENT WAKE SIGNATURE"

J. Aircraft, Vol. 46, No. 1, Jan.-Feb. 2009, pp. 263-268

The theoretical groundwork for the detection of any aircraft from its unique turbulent wake signature will be discussed, and practical methods to implement this theoretical result will be recommended. During the mid-1990's, NASA conducted research on the detection of atmospheric turbulence using light detection and ranging equipment. This light detection and ranging technology was able to detect turbulent disturbances by the Doppler shift in the frequency of laser-emitted energy that is scattered from atmospheric aerosols. Using this technology, the detection of turbulent disturbances physically created by the passage of aircraft through the atmosphere can be developed. In a military application, light detection and ranging turbulent detection would be able to spot the unconcealable turbulent disturbances caused by aircraft, thereby defeating current stealth technology. In addition, research suggests that turbulent wake generators (i.e., aircraft) have unique turbulent energy signatures. Using the principles of turbulent self-preservation, models can be created to predict both the Reynolds stress and momentum-defect signatures of aircraft as a function of their altitude and airspeed.

Garnier, F. and Laverdant, A.

"EXHAUST JET MIXING AND CONDENSATION EFFECTS IN THE NEAR FIELD OF AIRCRAFT WAKES"

Aerospace Science and Technology, Vol. 3, Issue 5, July 1999, pp. 271-280

To investigate the process of contrail formation, an integral model and a two-dimensional direct numerical simulation have been used to analyze the mixing and entrainment processes of the engine exhaust through their interaction with the vortex wake of various aircraft. The objective of this study is to evaluate the partial vapor pressure of water and temperature in the near field of subsonic and supersonic aircraft. Results are presented involving the saturation calculation by post-processing solution fields which provide a qualitative indicator of the condensation process. After testing the numerical algorithm with some success, this study was performed for three transport subsonic aircraft: A-330, B-737 and DC-9; for the twin-engine ATTAS of DLR and for the Anglo-French supersonic Concorde. For subsonic aircraft, in the early wake, the distance where saturation is reached depends only upon the engine jet characteristics. The engine jet location with respect to the vortex axis has an important influence on the mixing rate and on the saturation evolution. For the supersonic aircraft, a low saturation ratio has been shown along the plume centerline. The wing-tip vortices contribute largely to increase the mixing and dispersion of the exhaust plume. Consequently, the water saturation profiles are clearly changed by the vortical structure. Effects of the aerodynamic parameters are analyzed and discussed.

Garnier, F. and Laverdant, A.

"MODELING EXHAUST JET DILUTION IN AIRCRAFT WAKES: APPLICATION TO THE CONTRAIL FORMATION"

ICAS Paper No. 98-2.10.1, Sept. 1998, Melbourne, Australia.

To investigate the process of contrail formation, an integral model and a two-dimensional direct numerical simulation have been performed to analyze the mixing and entrainment processes of the engine exhaust through their interaction with the vortex wake of various aircraft. The objective of this study is to evaluate the partial vapor pressure of water and temperature in the near field of subsonic and supersonic aircraft. Results are presented involving the relative humidity calculation by post-processing solution fields and provide a qualitative indicator of the condensation process. After testing the numerical algorithm with some success, this study was performed for three transport subsonic aircraft: A-330, B-737 and DC-9; for twin-engine ATTAS of DLR and for the Anglo-French supersonic Concorde. For subsonic aircraft, in the early wake, the distance where the saturation is reached depends only upon the engine jet characteristics. For the supersonic aircraft, a low relative humidity has been shown in the plume centerline. However, the wing-tip vortices contribute largely to increase the mixing and dispersion of the exhaust plume. Consequently, the persistence or evaporation processes is clearly changed by the vortical structure. Effects of aerodynamic parameters are analyzed and discussed.

Garnier, F., Baudoin, C., Woods, P. and Louisnard, N.

"ENGINE EMISSION ALTERATION IN THE NEAR FIELD OF AN AIRCRAFT"

Atmospheric Environment, Vol. 31, No. 12, 1997, pp. 1767-1781

The objective of this paper, which constitutes a part of the AERONOX project, is the investigation of the potential transformation of the active species emitted from aircraft into reservoir species. The analysis is based on modeling of transformations of the near-field region, 1 km behind a Boeing 767 and a Boeing 747 aircraft. The processes considered are, firstly the dynamics of the jet flow and the jet-wing tip vortices interaction and secondly the potential chemical transformations of species such as NO, NO₂, HNO₂, HNO₃ and H₂SO₄. The wake dynamical processes are performed by using the 3D turbulent Navier-Stokes equations. Chemistry is calculated using a box model including the photochemical and heterogeneous reactions. In the jet flow, calculations have been performed for two engines CFM 56 and RB 211. Temperature fields and dilution profiles are compared. In the wake, the influence of the vortical motion on the inboard and outboard jet engines is shown. The chemical calculations show that there is a rapid disappearance of OH and HO₂ at the very beginning of the plume and simultaneous growth of HNO₂ and HNO₃. All the main chemical transformations are made in the hot jet flow. In the limits of the calculations, there is no significant chemical transformations during the first kilometer behind the Boeing 767, except for OH, HO₂ and CH₂O₂ whose concentrations appear highly dependent on the local exhaust NO_x concentration.

Garnier, F., Brunet, S. and Jacquin, L.

"MODELLING EXHAUST PLUME MIXING IN THE NEAR FIELD OF AN AIRCRAFT"

Ann. Geophysicae, Vol. 15, 1997, pp. 1468-1477

A simplified approach has been applied to analyze the mixing and entrainment processes of the engine exhaust through their interaction with the vortex wake of an aircraft. Our investigation is focused on the near field, extending from the exit nozzle until about 30 s after the wake is generated, in the vortex phase. This study was performed by using an integral model and a numerical simulation for two large civil aircraft: a two-engine Airbus 330 and a four-engine Boeing 747. The influence of the wing-tip vortices on the dilution ratio (defined as a tracer concentration) shown. The mixing process is also affected by the buoyancy effect, but only after the jet regime, when the trapping in the vortex core has occurred. In the early wake, the engine jet location (i.e. inboard or outboard engine jet) has an important influence on the mixing rate. The plume streamlines inside the vortices are subject to distortion and stretching, and the role of the descent of the vortices on the maximum tracer concentration is discussed. Qualitative comparison with contrail photograph shows similar features. Finally, tracer concentration of inboard engine centerline of B-747 are compared with other theoretical analyses and measured data.

Garnier, F., Gago, C. F. and Utheza, F.

"NUMERICAL SIMULATION OF LARGE-SCALE STRUCTURES IN EXHAUST JET/WAKE VORTEX MERGING"

AIAA Paper No. 2001-1039, Reno, NV, January 2001

This paper reports on a 3D temporal numerical simulation of the interaction between a jet flow and a trailing vortex. The simulation was performed from an experimental database of the vortex wake generated by a rectangular wing NACA0012 equipped with two jets beneath the airfoil. In this work, we focus on the 3D vorticity and scalar (initially included in the jet) fields in the vortex wake. The turbulence induced by the jet flow field interacts with the vortex, resulting in the large-scale structure generation outside the vortex core whereas the region very close to the core keeps its laminar state. The scalar field is subject to distortion and stretching inside the azimuthal vorticity tubes. The scalar concentration provides a reliable signature of where the helical instability occurs outside the vortex core. Later, the counter rotating vortices undergo a connection and consequently lose coherence in a very short time. The resulting scalar field concentrates then in small-scale eddies.

Garnier, F., Jacquin, L. and Laverdant, A.

"ENGINE JET ENTRAINMENT IN THE NEAR FIELD OF AN AIRCRAFT"

International Colloquium CAO on Impact of Aircraft Emissions upon the Atmosphere, October 1996, Clamart, France.

A simplified approach has been applied to analyze the mixing and entrainment processes of the engine exhaust through their interaction with the vortex wake of an aircraft. Our investigation is

focused on the near field, extending from the exit nozzle to the beginning of the vortex phase (i.e. to about 20 seconds after the wake is generated). This study is performed by using an integral model and a numerical simulation for a two-engine large civil aircraft. The properties of the wing-tip vortices on the calculation of the dilution ratio (defined as a tracer concentration) have been shown. The mixing process is also affected by the buoyancy effect, but only after the jet regime, when the trapping in the vortex core has occurred. Qualitative comparison with contrail photography shows similar features. Finally, the distortion and stretching of the plume streamlines inside the vortices can be observed, and the role of the descent of the vortices on the maximum tracer concentration has been discussed.

Garodz, L. J.

"ABBREVIATED FULL-SCALE FLIGHT TEST INVESTIGATION OF THE LOCKHEED L1011 TRAILING VORTEX SYSTEM USING TOWER FLY-BY TECHNIQUE"

Report FAA-AFS-I-76-1, June 1972, FAA NAFEC, Atlantic City, NJ.

A brief flight test program was performed at the National Aviation Facilities Experimental Center (NAFEC) to investigate the time-history characteristics of the vortex system of a Lockheed L1011 airplane in terminal area-type operations using a 140-foot-high instrumented tower. Vortex rotational flow velocities were measured by hot-film anemometers, vortex flow visualization -- as outlined by tower-mounted smoke grenades -- was documented, and meteorological data was recorded. In addition, data on aircraft track, performance, and configuration were gathered. The test results show that: (1) the L1011 vortex system was more persistent and intense than that of other heavy jet transport (300,000 lb) aircraft tested by NAFEC, but did not persist for more than 2 minutes; (2) vortex dissipation was due primarily to vortex breakdown (bursting); (3) vortex core diameters were on the average about 5, 4 and 2 feet in diameter for the landing, approach, and takeoff configurations, respectively; (4) peak recorded tangential velocities were 126, 135, and 224 feet per second for these same respective configurations; (5) vortex lateral movement in-ground effect was approximately $(\pi/6.6)b$, above ground level; and (6) average vortex descent velocities approached 6 feet per second out of ground effect.

Garodz, L. J.

"INVESTIGATION OF THE RELATIVELY LONG TIME-HISTORY CHARACTERISTICS OF THE CV-880 AIRPLANE IN TERMINAL AREA-TYPE FLIGHT OPERATIONS"

FAA Data Report, Project 504-303-03X, November 1970, NAFEC, Atlantic City, NJ

The CV-880 vortex characteristics were investigated using the tower fly-by and aircraft-mounted vortex flow visualization techniques. Tests were performed in takeoff, landing and holding (clean) configurations. General results were (1) vortex characteristics; i.e., intensity, persistence, and movement followed the same pattern with regard to aircraft configuration effects as noted and reported on previously for other aircraft; (2) vortex lateral movement in ground effect was about 47 feet AGL which approximates $(\pi/8)b$ for the CV-880; (3) the automatic 8-degree spoiler deflection on

the top of the wing combined with landing flap deflection of 55 degrees appeared to assist in producing low V -theta and in accelerating vortex dissipation; (4) an ambient wind velocity of 3 to 7 mph appears to be most conducive to vortex persistence within the first 100 feet above ground for takeoff and landing configurations; (5) vortices changed from an orderly to a random, turbulent-type flow in less than 2 minutes with some degree of flap deflection; and (6) CV-880 vortices for the conditions of these tests, were considered to have dissipated to insignificant velocities in less than 2,500 feet lateral travel under crosswind conditions.

Garodz, L. J.

"INVESTIGATION OF JET TRANSPORT AIRCRAFT VORTEX SYSTEMS DESCENDING INTO AND GENERATED IN GROUND EFFECT"

FAA Data Report, Project 504-303-03X, November 1970, NAFEC, Atlantic City, NJ.

Flight tests were performed with B-707, B-727, DC-9 and CV-880 to investigate the characteristics of vortex systems generated within ground effect and those generated out of but descending into ground effect. The tower fly-by technique was used. Aircraft passed upwind of the tower in takeoff, holding and landing configuration with the latter on a 2.75-degree glide-slope at 20-, 40-, 60-, 80-and 100-foot altitudes above ground level (AGL). General results were (1) vortices generated by aircraft with some degree of flap deflection tended to become unstable and degenerate to discontinuous, segmented-type vortices or a random-type motion in about 90 seconds; (2) a pulsating axial flow appears to signal the onset of vortex core disintegration; (3) for identical ages, there appears to be a drop-off in vortex tangential velocities as they are generated closer to the ground; (4) airflow sensors which were spaced at 10-foot intervals on the 100-foot tower were too far apart; and (5) with the exception of the DC-9/B-727 aircraft, flap deflection had a significant effect on V (max, vortex structure and life-span. As with previous tests, DC-9/B-727 vortex characteristics appeared to be independent of aircraft configuration and produced the highest V -theta, about 200 feet per second for the B-727.

Garodz, L. J.

"FEDERAL AVIATION ADMINISTRATION FULL-SCALE AIRCRAFT VORTEX WAKE TURBULENCE FLIGHT TEST INVESTIGATIONS: PAST, PRESENT, FUTURE"

AIAA Paper No. 1971-0097, New York, NY, 197.

This is a brief summary/status report on flight test programs which are designed to gather quantitative data on aircraft vortex characteristics for air traffic control application. Aircraft tested to date include the Sikorsky S-58 helicopter; the Boeing 747, 727 and 707; the Douglas DC8-63, DC8-33 and DC9-10; the Lockheed C5A, C-141; and the Convair CV-880 aircraft. Future vortex investigation flight tests will include the Douglas DC-10, Lockheed L1011 and the Concorde aircraft. Test techniques discussed are the aircraft tower fly-bys, vortex penetrations with suitably instrumented probe aircraft and vortex probing with an airborne rake-type airflow measurement system suspended from a second aircraft.

Garodz, L. J.

"MEASUREMENTS OF BOEING 747, LOCKHEED C5A AND OTHER AIRCRAFT VORTEX WAKE CHARACTERISTICS BY TOWER FLY-BY TECHNIQUES"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 265-285.

Flight tests have been conducted by the FAA at both the ESSA/AEC facility, Idaho Falls, Idaho, and the NAFEC, Atlantic City, New Jersey, during the period 18 February 1970 through 3 August 1970 to gather quantitative data on aircraft vortex wake characteristics using the tower fly-by technique. Aircraft tested included the Boeing 747, 707-300, and 727-100; the Douglas DC-8-63F, DC-8-33, and DC-9-10; the Lockheed C5A; the Convair 880; and the Learjet 24. A 200-foot and a 100-foot tower was used at the ESSA and NAFEC test sites, respectively. Vortex flow velocities were obtained using hot-film/hot-wire sensors.

Garodz, L. J.

"MEASUREMENTS OF THE VORTEX WAKE CHARACTERISTICS OF THE BOEING 747, LOCKHEED C5A AND OTHER AIRCRAFT"

FAA Data Report, Project 177-621-03X, April 1970, NAFEC, Atlantic City, N.

Flight tests were conducted at the Environmental Services Sciences Agency (ESSA) Site, Idaho Falls, Idaho, to investigate the vortices of the Boeing 747, 707, 727, Douglas DC-8 and DC-9, and the Lockheed C5A using the tower fly-by technique and a 200-foot tower. Flow visualization was provided by smoke grenades on the tower. In addition, CORVUS smoke oil was used on the B-747 and B-707 for vortex marking. Three-dimensional airflow measurement hot-wire sensors were mounted at 25-foot intervals up the tower. Atmospheric measurements were performed by ESSA. These tests revealed that (1) vortex core diameters are much smaller (almost an order of magnitude) than certain existing theories predicted; (2) vortex characteristics are significantly affected by air plane configuration, except for the clean wing B-727/DC-9. For the former, the vortex tangential velocities decreased with an increase in flap deflection. For the latter, the tangential velocities were independent of airplane configuration. V_{max} was about 140 ft/sec for the B-747/707/C5A in clean/low flap setting configuration and decreased to 60-100 ft/sec for the landing configuration, full flaps; (3) the B-727 vortices produced a distinct artillery shell-type whine as they passed overhead; (4) the primary vortex dissipation mode appeared to be bursting; (5) the vortices persisted for less than 2 minutes regardless of aircraft and configuration.

Garodz, L. J.

"HELICOPTER FLIGHT TESTS -- WAKE STUDIES AND ENCOUNTERS"

DOT/FAA/CT-81/206, March 1982, FAA, Atlantic City Airport, NJ.

The report describes a proposed program for a full-scale flight test investigation of helicopter vortex wake and downwash flow fields and helicopter response to an aircraft trailing vortex.

Garodz, L. J. and Clawson, K. L.

"VORTEX WAKE CHARACTERISTICS OF B757-200 AND B767-200 AIRCRAFT USING THE TOWER FLYBY TECHNIQUE"

ERL ARL-199, Vol. 1 and 2, January 1993, NOAA Air Resources Lab., Idaho Falls, ID

The number of large wing-mounted twin-engine jet transport aircraft in operation in the National Airspace System (NAS) has significantly increased over the past few years. Very little is known about the vortex wake characteristics of these aircraft, particularly in takeoff and landing configurations. Since aircraft classification and Air Traffic Control (ATC) separation criteria in terminal area flight operations are based primarily on the aircraft vortex wake hazard, the FAA undertook a flight test program in the fall of 1990 to investigate the vortex wakes of the Boeing 757-200 and 767-200. The tests were conducted at the NOAA vortex test facility near Idaho Falls, Idaho. This report presents the results of the flight tests using the tower flyby technique. Included are characterizations of vortex wakes as a function of aircraft configuration and performance, and ambient atmospheric conditions. Very high vortex tangential velocities were created by the B757 aircraft, with the most intense vortex measured at 326 feet per second (fps). Vortex velocities generated by the B757 were approximately 50% higher than those of the B767 at similar vortex ages younger than 60 seconds. The oldest vortices generated by the B757 were much younger than those generated by the B767, and were 84 and 135 s, respectively. The most intense vortices were generated under stable or near-neutral atmospheric conditions. Richardson Number, air temperature gradient, and wind speed were good general indicators of the Vmax-vortex age envelope. The 3-degree glide slope did not produce vortices that were statistically significantly greater in intensity.

Garodz, L. J. and Clawson, K. L.

"VORTEX CHARACTERISTICS OF C5A/B, C141B AND C130E AIRCRAFT APPLICABLE TO ATC TERMINAL FLIGHT OPERATIONS TOWER FLY-BY DATA"

NOAA Tech Memorandum ERL ARL-190, August 1991, Air Resources Lab., Silver Spring, MD.

During the spring of 1987, NOAA conducted a full-scale flight test program to investigate the vortex wake characteristics of the 3 primary USAF Military Airlift Command jet transport aircraft, namely, the Lockheed C5A/B Galaxy, the C141B Starlifter, and the C130B Hercules. The tower fly-by technique was employed for vortex data acquisition purposes. The FAA subsequently commissioned NOAA to reexamine the data with the objective of extending the existing knowledge of vortex behavior in terminal area flight operations. The FAA was particularly interested in the application of the data to Air Traffic Control separation standards. This report describes the results of that effort. Of significance in the reexamination of the USAF data was the length of vortex persistence even under somewhat turbulent or unstable atmospheric conditions. Although no vortex ages older than 2 minutes were

observed in the anemometer data, visual observations of vortex-entrained smoke indicated that C5A/B vortices persisted for as long as 3 minutes. Correlation of the Richardson Number with vortex persistence indicated the difficulty of using this atmospheric turbulence as an indicator of vortex decay. The effect of the high wing configuration of all three aircraft and the T-tail configuration of two of the aircraft on trailing vortex system characteristics is also discussed.

Garodz, L. J. and Miller, N. J.

"INVESTIGATION OF THE VORTEX WAKE CHARACTERISTICS OF JET TRANSPORTS DURING CLIMBOUT AND TURNING FLIGHT"

FAA AEQ-75-1, May 1975, NAFEC, Atlantic City, NJ

The characteristics of the trailing vortices of several large propeller and jet transport aircraft have been investigated by the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, N.J. This investigation centered around jet transport vortex persistence and movement during noise abatement-type departure operations at the Los Angeles International Airport and how approaching aircraft could avoid these vortices, however, it is concluded that the results and conclusions would be applicable to similar operations at other airports. The study is primarily based upon full-scale flight tests of vortex characteristics and their effect on encountering aircraft, conducted by NAFEC, NASA, Boeing, and the Royal Aircraft Establishment (RAE). Special flight tests for vortex investigations of the B-727 during noise abatement climb-outs, straightaway and turning flight, in takeoff and clean configuration are included. Vortex-generating aircraft included C5A, B-747, B-707, B-727, DC-7, CV-880 and Lincoln; vortex probe aircraft included CV-990, B-737, Learjet 23, DC-9 and Devon. A vortex avoidance zone was developed which has an active life of 2 minutes when below 5,000 feet above ground level and 2.6 minutes when higher than 5,000 feet above ground level.

Garodz, L. J. and Schutz, C. M.

"ANALYSIS OF LOW ATMOSPHERIC DENSITY WAKE TURBULENCE CHARACTERISTICS FOR JET TRANSPORT CATEGORY AIRCRAFT"

FAA Data Report, Project 177-621-04X, February 1968, NAFEC, Atlantic City, NJ.

The characteristics of the trailing vortices of several large jet transport aircraft operating at high altitudes at enroute speeds over the ocean were investigated by vortex flow visualization and penetration techniques. Flight tests were conducted from 29,000 to 38,000 feet. Vortex generators were a Lockheed C141, CV-880, Boeing C-135. Vortex penetrators included a C141, CV-880, Boeing C-135 and two specially instrumented Lockheed T-33 aircraft, one from National Aeronautical Establishment, Canada, and the other from NASA-Langley Research Center. Contrails were the primary means of vortex flow visualization except for the CV-880 wherein dumped dyed fuel was used. Separation distances between generator and penetrator ranged from 1,000 feet up to 8 nautical miles. It was found that (1) the contrails when they existed did indeed mark the trailing vortices for these model aircraft; (2) vortex turbulence induced on the probe aircraft ranged from moderate to severe; (3)

discrete vortices in the form of toroids, with high energy content, were observed and felt by the probe aircraft; and (4) compressor stall was experienced on three of the four C141 engines, and the fourth flamed out during an encounter at 1 nautical mile separation.

Garodz, L. J., Barber, M. R. and Kurkowski, R. L.

"FLIGHT TEST INVESTIGATION OF THE VORTEX WAKE CHARACTERISTICS BEHIND A BOEING 727 DURING TWO-SEGMENT AND NORMAL ILS APPROACHES"

FAA-NA-75-151, October 1975, FAA National Aviation Facilities Experimental Center, Atlantic City, NJ

A series of flight tests were performed to evaluate the vortex wake characteristics of a Boeing 727 (B727-200) aircraft during conventional and two-segment ILS approaches. Twelve flights of the B727, equipped with smoke generators for vortex marking, were flown wherein its vortex wake was intentionally encountered by a Lear Jet model 23 (LR-23) or a Piper Twin Comanche (PA-30); and its vortex location during landing approach was measured using a system of photo-theodolites. The tests showed that at a given separation distance there were no readily apparent differences in the upsets resulting from deliberate vortex encounters during the two types of approaches. Timed mappings of the position of the landing configuration vortices showed that they tended to descend approximately 91 meters (300 feet) below the flight path of the B727. The flaps of the B727 have a dominant effect on the character of the trailed wake vortex. The clean wing produces a strong, concentrated vortex. As the flaps are lowered, the vortex system becomes more diffuse. Pilot opinion and roll acceleration data indicate that 4.5 nautical miles would be a minimum separation distance at which roll control could be maintained during parallel encounters of the B727's landing configuration wake by small aircraft. This minimum separation distance is generally in scale with results determined from previous tests of other aircraft using the same roll control criteria.

Garodz, L. J., Hanley, W. J. and Miller, N. J.

"ABBREVIATED INVESTIGATION OF THE LOCKHEED L1011 AIRPLANE VORTEX WAKE CHARACTERISTICS IN TERMINAL AREA-TYPE OPERATIONS"

FAA Data Report, Project 214-741-04X, July 1972, NAFEC, Atlantic City, NJ

A brief flight test investigation was performed at the National Aviation Facilities Experimental Center (NAFEC) to investigate the time-history characteristics of the vortex system of the Lockheed L1011 Tri-Star jet transport airplane in terminal area-type operations using a 140-foot-high instrumented tower. Vortex rotational flow velocities were measured by hot-film anemometers, vortex flow visualization as outlined by tower-mounted smoke grenades was documented and meteorological data was recorded. Although only 19 tower fly-by passes were made, the test results showed that (1) the L1011 vortex system was more persistent and intense than other heavy jet transport (greater than 300,000 lbs.) aircraft tested by NAFEC but did not persist for more than 2 minutes; (2) vortex dissipation was primarily due to vortex instability (bursting); vortex core diameters were on the average of 5, 4 and 2 feet in diameter for the landing, approach and takeoff configurations, respectively; (4) peak-recorded

tangential velocities were 126, 135, and 224 feet per second for these same respective configurations; (5) a logarithmic model appeared to best describe the radial distribution of tangential velocities; (6) the upwind vortex was more intense and persistent than the downwind vortex for crosswind tests; (7) vortex lateral movement in ground effect was about $(\pi/6.6)b$ above ground level; and (8) average vortex descent velocities approached 6 feet per second out of ground effect.

Garodz, L. J., Hanley, W. J. and Miller, N. J.

"ABBREVIATED INVESTIGATION OF THE DOUGLAS DC-10 AIRPLANE VORTEX WAKE CHARACTERISTICS IN TERMINAL AREA-TYPE OPERATIONS"

FAA Data Report, Project 214-741-04X, August 1972, NAFEC, Atlantic City, NJ

The Douglas DC-10 Series 10 vortex characteristics were investigated using the tower fly-by technique. NAFEC's 140-foot-high vortex test tower was used. Hot-film airflow sensors at 1-foot intervals on the tower were used for tangential velocity measurements and smoke grenades for flow visualization. Wind velocity/direction and temperature were measured at 5 points on the tower. Twenty tower fly-bys were conducted in takeoff, approach, and landing configurations. Results indicated that (1) DC-10 vortex characteristics were similar to another wide-bodied jet, the L1011 which was previously tested; (2) multiple vortices were noted in the recorded data; (3) visually, vortex flow visualization revealed that the vortices underwent an instability mode and dissipated, primarily by bursting, in less than 2 minutes; (4) vortex tangential velocities of up to 192 feet per second were recorded (takeoff configuration); and (5) core diameters were relatively small - about 8 to 10 feet.

Garodz, L. J., Lawrence, D. M. and Miller, N. J.

"THE MEASUREMENT OF THE BOEING 747 TRAILING VORTEX SYSTEM USING THE TOWER FLY-BY TECHNIQUE"

FAA-RD-73-156, June 1974, NAFEC, Atlantic City, NJ

The characteristics of the trailing vortex system of the Boeing 747 airplane have been investigated by the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, N.J., during a series of flight tests conducted in September and October 1972. This investigation is part of a long-term program, started in February 1970 with flight tests conducted by NAFEC at the Atomic Energy Commission site at Idaho Falls, Idaho, devoted to the study of the overall wake turbulence problem. The present tests were conducted using improved flow measurement and meteorological instrumentation, permitting greater resolution than had been possible in earlier testing. Principal findings were that the peak tangential velocity decays as the reciprocal of the square root of the time elapsed since vortex generation; that the peak velocity is unaffected by the throttling back of the adjacent outboard engine; and that the lateral transport velocities correlate quite well with theory. Vortex descent rates did not correlate with theory, being up to three times greater than theoretical values.

Garodz, L. J., Lawrence, D. M. and Miller, N. J.

"THE MEASUREMENT OF THE BOEING 727 TRAILING VORTEX SYSTEM USING THE TOWER FLY-BY TECHNIQUE"

FAA-RD-74-90, August 1974, NAFEC, Atlantic City, NJ

The results are presented of a series of low altitude (100-300 feet above ground level) flight tests performed at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey, in which the trailing vortices of the Boeing 727 airplane were investigated, using a 140-foot tower instrumented with air velocity, direction, temperature, and humidity sensors. Flow visualization was also employed, using colored smoke streams and film records made. The airplane was tracked by the NAFEC Phototheodolite Facility. The data presented consists of plots of vortex tangential velocity distribution, peak tangential velocity as a function of time, airplane configuration, windspeed, and airplane altitude in proximity to the tower, vortex descent rates, lateral transport velocities, and specimen time histories of the velocities measured by individual sensors.

Garodz, L. J., Lawrence, D. M. and Miller, N. J.

"THE MEASUREMENT OF THE BOEING 707 TRAILING VORTEX SYSTEM USING THE TOWER FLY-BY TECHNIQUE"

FAA-RD-75-15, March 1975, NAFEC, Atlantic City, NJ

The results are presented for a series of low altitude (160-240 feet above ground level) flight tests performed at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey, in which the trailing vortices of the Boeing 707 airplane were investigated using a 140-foot tower instrumented with airspeed, velocity, direction, temperature, and humidity sensors. Flow visualization was employed and motion picture records made. The airplane was tracked by the NAFEC Phototheodolite Facility.

Garodz, L. J., Lawrence, D. M. and Miller, N. J.

"MEASUREMENT OF THE TRAILING VORTEX SYSTEMS OF LARGE TRANSPORT AIRCRAFT USING TOWER FLY-BY AND FLOW VISUALIZATION (SUMMARY, COMPARISON AND APPLICATION)"

FAA RD-75-127, May 1975, NAFEC, Atlantic City, NJ.

Full-scale flight test investigations have been made of the characteristics, persistence and movement of the trailing vortices generated by propeller and jet transport aircraft. The tests were performed by NAFEC, Atlantic City, N.J., during the period 1970-1973 using tower fly-by and vortex flow visualization. The results are summarized and comparisons made of the vortices of the Douglas DC-10, DC-9, and DC-7; Boeing 747, 727 and 707; Lockheed C5A, C141, and L1011; and the Convair 880 aircraft. Vortex mathematical models and decay mechanisms are discussed and their effects (upset potential) on encountering aircraft are investigated for possible air traffic control application.

Garodz, L. J., Lawrence, D. M. and Miller, N. J.

"THE MEASUREMENT OF THE MCDONNELL-DOUGLAS DC-9 TRAILING VORTEX SYSTEM USING THE TOWER FLY-BY TECHNIQUE"

FAA-RD-74-173, November 1974, NAFEC, Atlantic City, NJ

The results are presented of a series of low-altitude (approximately 200 feet above ground level) flight tests performed at NAFEC, Atlantic City, N.J., in which the trailing vortices of the McDonnell-Douglas DC-9 airplane were investigated, using a 140-foot instrumented tower. Flow visualization (colored smoke streams) was employed and film records made. The airplane was tracked by the NAFEC phototheodolite facility. Data presented consists of plots of vortex tangential velocity distribution, peak velocity as a function of time, airplane configuration and wind speed, vortex descent rates, and lateral transport rates. Principal findings were that (1) within the time period 30-100 seconds after vortex generation, the peak velocities within the vortices were bounded by the function $V_{\theta} = 396 \exp(-.0347t)$, with a half-life of 20 seconds; (2) vortex cores were uniformly small (1-2 feet) in both configurations tested (takeoff and landing), and little or no growth with time was found; (3) vortex lateral transport velocities correlated well with the crosswind measured at 140 feet; and (4) the presence of a temperature inversion markedly retarded the vortex descent rates. The highest peak recorded tangential velocity was 120-130 feet per second, found to occur in both configurations tested.

Garodz, L. J., Miller, N. J. and Lawrence, D. M.

"THE MEASUREMENT OF THE DC-7 TRAILING VORTEX SYSTEM USING THE TOWER FLY-BY TECHNIQUE"

FAA-RD-73-141, November 1973, NAFEC, Atlantic City, NJ

This report describes the technique and presents the results of a series of full-scale flight tests performed at NAFEC in September 1971, in which the wing trailing vortices of the Douglas DC-7 airplane were investigated by flying the airplane at low altitude, upwind of, and in close proximity to a 140-foot instrumented tower. Tower instrumentation consisted of hot-film anemometers located at 4-foot intervals and wind velocity and direction sensors. Vortex air flow visualization was by use of colored smoke. The aircraft was tracked by the National Aviation Facilities Experimental Center's Phototheodolite Facility. The data consists of tangential velocity distribution plots, peak recorded velocity as a function of time, airplane configuration and wind; vortex vertical and lateral transport velocities, and specimen time histories of the velocities recorded at individual sensors. The principal findings were: (1) Peak absolute velocity, associated with the vortex core decays exponentially; (2) Vertical transport velocities of the vortices do not correlate well with those predicted by potential flow theory; (3) Lateral transport velocities correlate fairly well with values obtained from theory; and (4) The resolution possible with 4-foot spacing of the hot-wire anemometer is insufficient to precisely define vortex core size of the subject airplane.

Garry, K., Di Pasquale, D., Prince, S. and Lawson, N. J.

"THE INFLUENCE OF HIGH-SPEED SPIV DATA PROCESSING PARAMETERS ON AIRCRAFT WING VORTEX WAKE ASSESSMENT"

31st Congress of the International Council of the Aeronautical Sciences (ICAS 2018), September 2018, Belo Horizonte, Brazil.

This paper uses Stereoscopic Particle Image Velocimetry (SPIV) data from the near wake of a detailed sub-scale 1/2 model of a representative transport aircraft wing with leading and trailing edge high lift systems and outboard aileron representation, to analyze the influence of data-sampling period and frequency on the magnitude and position of the vortices resolved within the wake. The paper also evaluates the extent of vortex 'wander' at various stages of development within the near wake and offers guidance for optimum time-averaging strategy when investigating complex longitudinal vortex interaction studies in similar flow fields.

Garten, J. F.

"AN INVESTIGATION OF THE EFFECTS OF ENVIRONMENTAL STRATIFICATION AND SHEAR ON THE EVOLUTION OF VERTICALLY-PROPOGATING VORTEX PAIRS"

Ph.D. Thesis, 1997, Univ. of Colorado, Boulder, CO

The trailing vortices which roll up behind an aircraft and descend downwards through the atmosphere can pose considerable danger to other nearby aircraft. There is therefore longstanding practical interest in how counter-rotating vortex pairs evolve under a variety of ambient conditions. The effects of stratification, mean shear, and turbulence on the evolution are of particular interest, as their dynamical consequences can result in a wide range of possibilities, from a vortex pair rapidly dissipating to coherent structure emerging and surviving for very long periods. The results of direct numerical simulations of vortex pairs evolving under a variety of ambient conditions are presented and analyzed here. It is shown that weak stratification can lead to acceleration of a laminar vortex pair, while strong stratification can result in a vortex pair not propagating a significant vertical distance before being dissipated while exciting a complex collection of internal waves. The high numerical resolution requirements of these direct numerical simulations make it impossible to include realistic turbulent effects; however, weakly imposed perturbations within the initial flow field of a vortex pair are found to lead to instability processes which significantly alter the evolution. A mean shear of uniform vorticity is found to result in the rotation of the vortex pair, and this rotation initiates an instability process which can potentially lead to the eventual emergence of a solitary vortex. The results of preliminary direct numerical simulations of fully three-dimensional vortex pairs are also discussed, and they indicate that three-dimensional processes such as the Crow instability and vortex ring formation occur on long enough time scales that some of the previously discussed two-dimensional effects (due to ambient stratification and/or mean shear) may in part or whole persist.

Garten, J. F., Arendt, S., Fritts D. C. and Werne, J.

"DYNAMICS OF COUNTER-ROTATING VORTEX PAIRS IN STRATIFIED AND SHEARED ENVIRONMENTS"

J. Fluid Mech., Vol. 361, 1998, pp. 189-236

The evolution of a vertically propagating vortex pair in stratified and sheared environments is studied with a two-dimensional numerical model. We consider a range of Froude (Fr) and Richardson (Ri) numbers, and a limited number of Reynolds numbers (Re). We find that stratification causes the formation of counter-sign vorticity around each of the original vortices through baroclinic production. At higher Fr , this wake vorticity advects the primary vortices closer together, decreasing their separation distance and increasing their vertical propagation speed, as predicted by Crow (1974) and Scorer & Davenport (1970). For these higher values of Fr , the wake vorticity also participates in an instability of the primary vortex pair, with the direction of propagation of the pair oscillating about the vertical. We term this instability the vortex head instability to distinguish it from the jet instabilities to which the wake itself is also susceptible. At lower Fr , internal gravity wave radiation dominates, and the intensity and spatial coherence of each vortex is rapidly reduced. When a mean horizontal flow having constant shear is present in an unstratified fluid, we find that the vortices eventually rotate about one another with the same rotational sense as the background shear flow, as predicted in Lissaman et al. (1973). When stratification is also present, we find that the distribution of baroclinically generated wake vorticity is asymmetric, which sometimes leads to the emergence of a solitary vortex with the same sign as the background shear vorticity (depending on the values of Fr , Ri , and Re). Our limited survey of parameter space indicates that a solitary vortex emerges more rapidly for smaller values of Ri , smaller values of Fr , and/or larger values of Re .

Garten, J. F., Werne, J., Fritts, D. C. and Arendt, S.

"THE EFFECTS OF AMBIENT STRATIFICATION ON THE CROW INSTABILITY AND SUBSEQUENT VORTEX RECONNECTION"

Proceedings of Third International Workshop on Vortex Flows and Related Numerical Methods, ESAIM, Vol. 7, 1999, pp. 151-160

Discussed are the results of direct numerical simulations of three-dimensional anti-parallel vortex pairs evolving in ambient stratification for a range of Reynolds and Froude numbers. These results have relevance to both the study of aircraft trailing vortices, which can pose considerable hazard to following aircraft, and the general topic of vortex reconnection, an important process in fully-developed turbulence and other complex flows.

Garten, J. F., Werne, J., Fritts, D. C. and Arendt, S.

"DIRECT NUMERICAL SIMULATIONS OF THE CROW INSTABILITY AND SUBSEQUENT VORTEX RECONNECTION IN A STRATIFIED FLUID"

Journal of Fluid Mechanics, Vol. 426, January 2001, pp. 1-45.

The evolution of a vertically propagating three-dimensional vortex pair in ambient stratification is studied with a three-dimensional numerical model. We consider a range of Reynolds (Re) and Froude (Fr) numbers, and initialize the vortex pair in a configuration that promotes growth of the Crow instability (Crow 1970). The growth rate of the instability is Re dependent, and we present a method for extending Crow's model to predict this dependence. We also find that relatively strong ambient stratification (Fr less than or equal to 2) further alters the growth of the instability via advection by baroclinically produced vorticity. For all of our cases with Fr greater than or equal to 1 (including our unstratified cases where Fr goes to infinity), the instability leads to vortex reconnection and formation of a vortex ring. A larger Re delays the commencement of the reconnection, but it proceeds more rapidly once it does commence. We compute a reconnection time scale (t), and find that $t \sim 1/Re$, in agreement with a model formulated by Shelley et al. (1993). We also discuss a deformative/diffusive effect (related to yet distinct from the curvature reversal effect discussed by Melander and Hussain 1989) which prevents complete reconnection. Ambient stratification (in the range Fr greater than or equal to 1) accelerates the reconnection and reduces t by an amount roughly proportional to $1/Fr$. For some Fr , stratification effects overwhelm the deformation effect, and complete reconnection results.

Gartrell, L. R. and Jordan, Jr., F. L.

"DEMONSTRATION OF RAPID-SCAN TWO-DIMENSIONAL LASER VELOCIMETRY IN THE LANGLEY VORTEX RESEARCH FACILITY FOR RESEARCH IN AERIAL APPLICATIONS"

NASA TM 74081, August 1977, NASA Langley Research Center, Hampton, VA

Tests were conducted to demonstrate a rapid scan two-dimensional laser velocimeter (LV) measurement technique for aerial applications research. The LV system is capable of simultaneously measuring both vertical and axial flow velocity components in a near or far field vortex system. Velocity profiles were successfully measured in the wake vortex of a representative agricultural aircraft model, with the vortex system rapidly transporting in ground effect. Results indicate that the laser velocimetry technique can provide quantitative information of wake vortex characteristics in ground effect.

Gartrell, L. R. and Rhodes, D. B.

"A SCANNING LASER-VELOCIMETER TECHNIQUE FOR MEASURING TWO-DIMENSIONAL WAKE-VORTEX VELOCITY DISTRIBUTIONS"

NASA TM-1661, May 1980, NASA Langley Research Center, Hampton, VA

A rapid scanning two-dimensional laser velocimeter (LV) has been used to measure simultaneously the vortex vertical and axial velocity distributions in the Langley Vortex Research Facility. This system utilized a two-dimensional Bragg cell for removing flow direction ambiguity by translating the optical frequency for each velocity component, which was separated by band-pass filters. A rotational scan mechanism provided an incremental rapid scan to compensate for the large displacement of the vortex with time. The data were processed with a digital counter and an on-line minicomputer. Vaporized

kerosene (0.5 micron to 5-micron particle sizes) was used for flow visualization and LV scattering centers. The overall measured mean-velocity uncertainty is less than 2 percent. These measurements were obtained from ensemble averaging of individual realizations.

Gasich, W. E.

"THE DOWNWASH DISTRIBUTION BEHIND A WING WITH AN ANGLE OF ATTACK DISCONTINUITY AT SUPERSONIC SPEEDS"

Aeronautical Engineer Thesis, June 1948, California Institute of Technology, Pasadena, CA.

Investigation of the downwash field behind a wing with an angle of attack discontinuity at supersonic speeds by use of linearized conical flow theory has shown the downwash to be of finite magnitude at all points in and behind the plane of the wing. The downwash at more than five chord lengths behind the wing was found to asymptotically approach the value of downwash calculated in the Trefftz plane. Behind the wing and in the span that is determined by the intersection of the Mach cones from the leading edge with the trailing edge, an inexplicable action of the downwash was found to exist. It was found that at the trailing edge the downwash was a 100 percent of that on the wing surface. At two chord lengths, the downwash was 83 percent. Upon moving aft, it was found that the downwash increased in magnitude and that at 10 chord lengths, it asymptotically approached the value at the Trefftz plane, namely 100 percent again. By considering an idealized missile configuration, it was found that roll-reversal was possible. The possibility of reversal was found to be almost entirely dependent upon the location of the control lifting surfaces with respect to one another. A brief reference to the sidewash field was made, since the values of sidewash were a natural outgrowth of the solution of the downwash field in the Trefftz plane. An elementary consideration of the sidewash field also showed a contribution to an induced rolling moment that tends to produce roll reversal.

Gatto, A., Bourdin, P. and Friswell, M. I.

"EXPERIMENTAL INVESTIGATION INTO ARTICULATED WINGLET EFFECTS ON FLYING WING SURFACE PRESSURE AERODYNAMICS"

Journal of Aircraft, Vol. 47, No. 5, September-October 2010, pp. 1811-1815.

The use of articulated winglets on a baseline swept wing configuration to influence the surface pressure aerodynamics of a model flying wing has been experimentally investigated in this Note. From the surface pressure data taken from the upper wing and winglet surfaces, there is a substantial influence of winglet dihedral position on the main wing surface pressure. The ability of this concept to adjust and tailor this aerodynamic loading toward the main wing tip may provide useful application to second-order performance and efficiency enhancements such as gust load alleviation.

Gatto, A., Mattioni, F. and Friswell, M. I.

"EXPERIMENTAL INVESTIGATION OF BISTABLE WINGLETS TO ENHANCE WING LIFT TAKEOFF CAPABILITY"

Journal of Aircraft, Vol. 46, No. 2, March-April 2009, pp. 647-655.

An experimental investigation into the use of a bistable winglet to enhance the lift characteristics of a wing transitioning from lower to higher subsonic flow speeds is presented in this paper. The concept centers around the use of a specifically designed composite winglet, manufactured with an unsymmetric layup, which, when increasingly loaded, snaps between two stable states. Initially, during low-speed operation, the winglet is fixed in one stable state that is specifically designed to be cambered, thus enhancing the lift capability of the wing. At higher dynamic pressures, the winglet snaps to a configuration more intuitive and conventional to current winglet design. Results presented in this paper show the concept to be viable at enhancing the lift produced by a swept wing as aerodynamic loading increases before snap-through. During snap-through, however, the absence of any method of controlling the snap-through process generated significant dynamic loading that was transmitted, unhindered, throughout the entire test rig.

Gausz, T.

"BLADE VORTEX INTERACTION PROBLEM AT HELICOPTER ROTORS"

Conf. on Modelling Fluid Flow (CMFF'03), 12th International Conf. on Fluid Flow Technologies, Sept. 2003, Budapest, Hungary.

The helicopter rotor blade excites a vortex system, which consists of bound, trailed and shed vortices. The trailed and shed vortices roll up to the blade tip vortex. This strong tip vortex has a remarkable induced velocity field, which can cause pregnant changes in the aerodynamic loads of the rotor blade. This tip vortex moves together with the ambient air masses. Arises a 'Blade Vortex Interaction' (BVI) problem when this tip vortex moves closely to a rotor blade. To get physically real induced velocity field a real vortex model with finite core must be applied.

Gautier, W., Stehle, A., Schonlinner, B., Prechtel, U. and Manzel, W.

"ANTENNA ARRAYS FOR RF-MEMS BASED 77 GHZ ON-BOARD WAKE VORTEX DETECTION SENSOR"

2nd International ITG Conf. on Antennas, INICA '07, March 2007, pp. 217-221

In this paper the first generation of transmit and receive antennas for an on-board wake vortex detection front end module at 76.5 GHz is presented. The antennas are realized with serially fed patch antenna arrays connected in parallel by a corporate feed network. The use of RF-MEMS phase shifters between the feed network and the 2D patch antenna arrays will, in a future integration step, allow for steering the receive antenna beam in discrete steps in the horizontal plane. The principle of operation of the front-end module and the design of both antennas are described. Simulated and measured results are presented to validate the design.

Gayet, J.-F., Shcherbakov, V., Voigt, C., Schumann, U., Schauble, D., Jessberger, P., Petzold, A., Minikin, A., Schlager, H., Dubovik, O. and Lapyonok, T.

"THE EVOLUTION OF MICROPHYSICAL AND OPTICAL PROPERTIES OF AN A380 CONTRAIL IN THE VORTEX PHASE"

Atmospheric Chemistry and Physics, Vol. 12, 2012, pp. 6629-6643.

A contrail from a large-body A380 aircraft at cruise in the humid upper troposphere has been probed with in-situ instruments onboard the DLR research aircraft Falcon. The contrail was sampled during 700 s measurement time at contrail ages of about 1-4 min. The contrail was in the vortex regime during which the primary wake vortices were sinking 270 m below the A380 flight level while the secondary wake remained above. Contrail properties were sampled separately in the primary wake at 90 and 115 s contrail age and nearly continuously in the secondary wake at contrail ages from 70 s to 220 s. The scattering phase functions of the contrail particles were measured with a polar nephelometer. The asymmetry parameter derived from these data is used to distinguish between quasi-spherical and aspherical ice particles. In the primary wake, quasi-spherical ice particles were found with concentrations up to 160 per cubic cm, mean effective diameter D of 3.7 microns, maximum extinction of 7.0 inverse km, and ice water content (IWC) of 3 mg per cubic m at slightly ice-subsaturated conditions. The secondary and primary wakes were separated by an almost particle-free wake vortex gap. The secondary wake contained clearly aspherical contrail ice particles with mean D of 4.8 microns, mean (maximum) concentration, extinction, and IWC of 80 (350) per cubic cm, 1.6 (5.0) inverse km, and 2.5 (10) mg per cubic m, respectively, at conditions apparently above ice-saturation. The asymmetry parameter in the secondary wake decreased with contrail age from 0.87 to 0.80 on average indicating a preferential aspherical ice crystal growth. A retrieval of ice particle habit and size with an inversion code shows that the number fraction of aspherical ice crystals increased from 2 percent initially to 56 percent at 4 min contrail age. The observed crystal size and habit differences in the primary and secondary wakes of an up to 4 min old contrail are of interest for understanding ice crystal growth in contrails and their climate impact. Aspherical contrail ice particles cause less radiative forcing than spherical ones.

Gee, D., Paillet, F. and Kurylowich, G.

"ANALYSIS OF A WAKE TURBULENCE HAZARD IN USAF OPERATIONS (T-39 ACCIDENT)"

AFFDL-TM-75-19-FGC, January 1975, Air Force Flight Dynamics Lab; Wright-Patterson Air Force Base, OH. (for official use only)

Analyses related to the investigation of a T-39 accident are presented which appeared caused by an encounter with the wake of a DC-10. Wake propagation and dynamic encounter numerical simulations are compared to the pilots' statements and other relevant facts. The necessary existence of an inversion layer which could prevent the rapid descent of the DC-10 wake is also noted.

Gehlert, P., Cafiero, G. and Vassilicos, J. C.

"EFFECT OF FRACTAL ENDPLATES ON THE WINGTIP VORTEX"

AIAA Paper 2018-1796, January 2018, Kissimmee, FL.

An experimental investigation was performed on the effect of fractal endplates on the wingtip vortex of a NACA 0012 semi span wing at a Reynolds number of 200,000. The endplates were obtained by introducing three different fractal patterns. Constant temperature anemometry and stereoscopic particle image velocimetry were employed to assess both the local flow properties as well as the spatial organization of the wingtip vortex. The results show that the introduction of a fractal endplate strongly affects both the geometry and the turbulence features of the vortex. In particular, it is found that the fractal geometry weakens the vortex by spreading the turbulent kinetic energy over a broader range of frequencies. We relate this loss of coherence to a faster dissipation of the vortex, thus paving the way to the employment of fractal endplates to reduce the hazard associated to such flow features.

Geister, D. and Geister, R.

"INTEGRATING UNMANNED AIRCRAFT EFFICIENTLY INTO HUB AIRPORT APPROACH PROCEDURES"

NAVIGATION: Journal of the Institute of Navigation, Vol. 60, No. 3, Fall 2013, pp. 235-247.

Future Aircraft Surveillance Application (ASA) systems for situational awareness applications (e.g., conflict detection and resolution, final approach and runway occupancy awareness, and airport surface situational awareness methods), airborne spacing applications, airborne separation applications, and self-separation applications will benefit from the introduction of Automatic Dependent Surveillance-Broadcast (ADS-B). An alternative ADS-B implementation, which transmits measurements from the Global Navigation Satellite System (GNSS) instead of aircraft state vectors and performance parameters in the current implementation, has been proposed previously to improve surveillance performance. This paper summarizes the proposed methodology, discusses its threat models and integrity aspects, and presents the initial flight test results of this alternative ADS-B implementation, along with a performance analysis.

Gentry, M. C. and Jacobi, A. M.

"HEAT TRANSFER ENHANCEMENT BY DELTA-WING VORTEX GENERATORS ON A FLAT PLATE: VORTEX INTERACTIONS WITH THE BOUNDARY LAYER"

Experimental Thermal and Fluid Science, Vol. 14, 1997, pp. 231-242.

New data are presented that demonstrate a 50 to 60 percent enhancement of average heat and mass transfer for flow over a flat plate at low Reynolds numbers, using delta-wing vortex generators. The mechanisms responsible for the enhancement are determined, and a single parameter for estimating their effect is established. Using a straightforward method for evaluating this parameter from flow visualization data, optimal delta-wing geometries were found for Reynolds numbers of 600, 800, and 1000 based on wing-chord length. The results were also used to develop a clearer understanding of the interactions between the vortex and boundary layer. When a high-circulation vortex is placed near the edge of the boundary layer, it effectively thins the boundary layer; the vortex advects free-stream fluid into the temperature or species boundary layer. Vortices should be generated in a common inflow arrangement so that induced velocities keep the vortices near the boundary layer.

George, M., Kisielowski, E. and Douglas, D. S.

"INVESTIGATION OF THE DOWNWASH ENVIRONMENT GENERATED BY V/STOL AIRCRAFT OPERATING IN GROUND EFFECT"

Technical Report 68-52, July 1968, Dynasciences Corp., Blue Bell, PA.

Analytical methods are developed for determining the downwash environment generated by multirotor/propeller V/STOL aircraft configurations operating in ground proximity. These methods are utilized to compute rotor flow field and contaminant dust cloud characteristics (including particle density and size distributions) for the H-21, XC-142, X-22A, X-19A, and XV-5A aircraft. The effects of the contaminated atmosphere on pilot's visibility, ground equipment, and personnel are also determined for these aircraft. The theoretically predicted results are generally in good agreement with the limited test data. Additional full-scale test data are required to verify further the assumptions inherent in the theory.

George, R. and Yang, J.

"A SURVEY FOR METHODS OF DETECTING AIRCRAFT VORTICES"

ASME Paper DETC2012-70632, August 2012, Chicago, IL.

Wake vortices produced by the lifting surfaces of large aircraft can have catastrophic effects on aircraft that follow too close behind. Many incidents have been blamed on wingtip vortices in the past several decades. Therefore, vortex detection is important for enhancing airport productivity by allowing adoptive spacing and for increasing the safety of all aircraft operating around the airport by alerting controllers that hazardous conditions may exist near the runways. Many methods have been developed for detecting wake vortices. However, there is a lack of a literature review to summarize all the methods and compare their advantages and drawbacks. Thus, the purpose of this paper is to review these technologies and to summarize their strengths and weaknesses. There are two main methods available in the literature: active and passive detection methods. Active detection methods include LIDAR (LIGHT Detection and Ranging), RADAR (Radio Detection and Ranging), and SODAR (Sonic Detection and Ranging). Passive detection methods include microphone systems, opto-acoustic systems, and ultrasonic detection of circulation. Although vortex detection methods are available, due to military and scientific usage, many researchers are still investigating new methods that are more effective.

Georges, L., Allen, A., Melber-Wilkending, S., Louagle, T., Breitsamter, C. and Geuzaine, P.

"WAKE VORTICES GENERATED BY AN AIRCRAFT FUSELAGE: COMPARISON OF WIND TUNNEL MEASUREMENTS ON THE TAK MODEL WITH RANS AND RANS-LES SIMULATION"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

The first objective of the present study is to identify the proper influence of the fuselage to the global wake of a complete aircraft. The second objective is to investigate the ability of different numerical approaches to properly compute the near-field wake. The selected geometry is a generic 4-engines civil aircraft, the TAK model of TUM, where windtunnel hot-wire measurements have been performed. On the one hand, the DLR realized RANS simulations using the TAU code. On the other hand, Cenaero performed RANS simulations using the Spalart-Allmaras model and unsteady RANS-LES computations by way of the standard DES model. The vorticity field in a plane located just behind the fuselage tail is studied; the different approaches capture successfully the three main wake vortices. The present investigation showed that for this low-Mach application, the spatial discretization has a larger influence on the solution quality than the turbulence modelling approach. Furthermore, for the angle of attack and the geometry considered, the DES approach produced a steady wake: in experiments, unsteady turbulent structures are present but they are far smaller in size than the large scales of the flow, so that the meshes used in DES were too coarse to capture those small fluctuations.

Georges, L., Bricteux, L., Duponcheel, M., Geuzaine, P. and Winckelmans, G.

"LES OF WAKE VORTICES IN GROUND EFFECT WITHOUT AND WITH WIND, AND ALSO COMPARING DIFFERENT MULTISCALE SUBGRID MODELS"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008.

Cenaero and the UCL performed LES calculations of a two-vortex system in ground effect. A two-vortex system placed close to the ground generated boundary layers at the ground due to the no slip condition. These boundary layers are subject to an adverse pressure gradient that finally leads to their separation. A secondary counter-rotating vortex system is then generated that interacts strongly with the primary one. In fact, the secondary vortices are first orbiting around the primary vortices and are prone to short-wavelength instabilities that grow quickly in time. Finally, these three-dimensional instabilities are trapped by the primary vortices so that a strong interaction occurs between both vortex systems, eventually leading to a complex turbulent flow. The first objective of the present study was to investigate the influence of the Reynolds number by increasing it to 20000, a Reynolds number that is expected to be high enough to be representative of very high Reynolds number configurations. This work was done using wall-resolved LES on a 33-million node non-uniform cartesian mesh and a fourth-order accurate finite differences incompressible flow solver. The second objective of the study was to investigate the influence of the atmospheric conditions. Keeping the Reynolds number unchanged, this was done by superimposing three-dimensional time-dependent turbulent winds to the initial vortex pair.

Georges, L., Geuzaine, P., Duponcheel, M., Bricteux, L., Lonfils, T. and Winckelmans, G.

"LES OF TWO-VORTEX SYSTEM IN GROUND EFFECT (LONGITUDINALLY UNIFORM WAKES)"

AST4-CT-2005-012238, CENAERO, Charleroi, Belgium, October 2006

This document reports about the large eddy simulation (LES) of a two-vortex system in ground effect, at a Reynolds of 20000. Two 'wall-resolved' LES, using different sub-grid scale (SGS) models, have been performed. The results will show the importance of the SGS modeling on the vortex system evolution. First, a LES with a Smagorinsky model supplemented by a Piomelli damping function in the near-wall region is selected; the main reason being that this model is rather standard. Secondly, an advanced modeling strategy, based on an approach with flow scales discrimination, is investigated. This better method prevents the over-diffusive behavior of the classical Smagorinsky model in the vortex cores.

Georges, T. M.

"ACOUSTIC RAY PATHS THROUGH A MODEL VORTEX WITH A VISCOUS CORE"

Journal of the Acoustical Society, Vol. 51, No. 1, January 1972, pp. 206-209

Angular deflection and the formation of a line caustic are examined for acoustic waves passing through a cylindrical vortex with a viscous core. Ray paths are displayed in normalized form and appear to be applicable to the aircraft-wake problem as well as to long-distance sound propagation through synoptic weather features.

Gerhardt, H. A.

"WINGTIP VORTEX DEVICE FOR INDUCED DRAG REDUCTION AND VORTEX CANCELLATION"

US Patent 5,934,612, August 1999.

The present invention is a wingtip vortex device for induced drag reduction and vortex cancellation. The wingtip vortex device is an aerodynamic drag reduction system installed at the wingtips of an aircraft. The wingtip vortex device comprises an impeller located ahead of the wingtip chord, a wind turbine device located behind the wingtip chord, and an intermediate gear device for coupling the impeller with the wind turbine and/or for generating power. Thus, the wingtip vortex device is self-contained as the impeller is powered by the vortex-driven turbine. As a result, induced drag is reduced without requiring an external power source such as the aircraft propulsion system.

Gerontakos, P. and Lee, T.

"NEAR WAKE BEHIND AN AIRFOIL WITH LEADING-EDGE FLOW CONTROL"

Journal of Aircraft, Vol. 42, No. 2, March-April 2005, pp. 561-568

The effect of leading-edge cylinder rotation on the near wake behind a NACA 0015 airfoil was investigated. The results show that 1) depending on the magnitude of the rotation speed, the structure of the vortical wake could be substantially modified and a variety of vortex-shedding modes (e.g., the regular Karman vortex-shedding mode and also its combination with a single vortex pairing in each half of vortex-shedding cycle, the nearly parallel vortex-shedding mode, and the locally and globally stable modes), in addition to the expected delay in the boundary-layer flow separation, were observed; 2) the

location of inception of the Karman-type vortex-shedding mode moved upstream with increasing cylinder rotation; 3) the frequency of the vortex shedding, or the number of shed vortices, decreased with increasing cylinder rotation; 4) the vortex strength was found to decrease with the cylinder rotation and was weaker than that of a baseline airfoil; and 5) the longitudinal spacing of the shed vortices was found to be a strong function of the cylinder rotation while the lateral spacing a weaker function. Moreover, the presence of a leading-edge rotating cylinder with no rotation rendered no noticeable increase in the wake width and drag. However, with an increase in cylinder rotation the separation of the boundary layer was delayed, and the wake width and deficit were reduced.

Gerontakos, P. and Lee, T.

"EFFECTS OF WINGLET DIHEDRAL ON A TIP VORTEX"

Journal of Aircraft, Vol. 43, No. 1, January-February 2006, pp. 117-124

The effect of winglet dihedral on the near-field tip vortex flow structure behind a swept and tapered NACA 0015 wing was investigated at $Re = 1.81 \times 100,000$. The winglet dihedral led to a significantly reduced (increased) peak tangential velocity and vorticity (core radius) compared to a baseline wing. The values of core circulation (core axial velocity) could be below or above the baseline-wing value, depending on the winglet angle, and exhibited a local maximum (minimum) at winglet dihedral = 0 deg. The inner region of the tip vortex flow exhibited a self-similar behavior for a wing with and with no winglet. The lift-induced drag was always reduced by the addition of a winglet. The negative dihedral was more effective in reducing the lift-induced drag compared to the corresponding winglet of positive dihedral. A large discrepancy in the lift-induced drag was, however, observed between the wake integral method and the classical lifting-line theory.

Gerontakos, P. and Lee, T.

"EFFECTS OF WINGLET DIHEDRAL ON A TIP VORTEX"

Journal of Aircraft, Vol. 43, No. 1, January - February 2006, pp. 117-124

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Gerontakos, P. and Lee, T.

"NEAR-FIELD TIP VORTEX BEHIND A SWEPT WING MODEL"

Experiments in Fluids, Vol. 40, 2006, pp. 141-155

The near-field flow structure of a tip vortex behind a sweptback and tapered NACA 0015 wing was investigated and compared with a rectangular wing at the same lift force and $Re = 181,000$. The tangential velocity decreased with the downstream distance while increased with the airfoil incidence. The core radius was about 3% of the root chord regardless of the downstream distance and angle of attack less than 8 deg. The core axial velocity was always wake-like. The core circulation and total circulation of the tip vortex remained nearly constant up to $x = 3.5 \times$ root chord and had a ratio of 0.63. The total circulation of the tip vortex accounted for only about 40% of the bound root circulation. For a rectangular wing, the axial flow exhibited islands of wake- and jet-like velocity distributions with Core circulation/Total circulation = 0.75 and Total circulation/Bound root circulation = 0.70. For the sweptback and tapered wing tested, the inner region of the tip vortex flow exhibited a self-similar behavior for x greater than or equal to the root chord. The lift force computed from the spanwise circulation distributions agreed well with the force-balance data. A large difference in the lift-induced drag was, however, observed between the wake integral method and the inviscid lifting-line theory.

Gerontakos, P. and Lee, T.

"ACTIVE TRAILING-EDGE FLAP CONTROL OF OSCILLATING-WING TIP VORTEX"

AIAA Journal, Vol. 44, No. 11, November 2006, pp. 2746-2754

The tip vortex generated by an oscillating NACA 0015 wing with a moveable trailing-edge flap was investigated at $Re = 1.65 \times 100,000$ by using a miniature triple hot-wire probe. Both positive and negative flap deflections, actuated at different start times, were tested. The negative flap motion was found to be most effective in displacing the vortex position with earlier actuation leading to larger vertical vortex displacements. Negative flap deflections strengthened the vortex, moved the centroid further outboard, decreased the peak vorticity, and increased the vortex size. The positive trailing-edge flap motion, however, resulted in a more concentrated tip vortex of reduced vortex strength located further inboard. The lift-induced drag was decreased (increased) for positive (negative) trailing-edge flap, compared to a baseline wing.

Gerz, T.

"ATMOSPHERIC IMPACT ON WAKE VORTEX DEVELOPMENT"

European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS 2004, Jyväskylä, Finland, July 2004

A robust wake vortex warning system needs to predict the decay and transport of aircraft vortices along the glide path. Besides a validated, real-time wake vortex transport and decay model, such a system requires highly resolved forecast and measurement data of meteorological quantities as vertical

profiles of wind, turbulence kinetic energy, eddy dissipation rate, and temperature. To this end, wake vortex forecasting and measuring campaigns have been accomplished. The objective was to test the components of the weather and wake vortex monitoring and prediction system as the local weather forecast model NOWVIV, the wake transport and decay model P2P, the lidar as a wake detecting and characterizing tool. NOWVIV predicts the profiles of wind, virtual potential temperature, and turbulent kinetic energy around the airfield for 24 hours. These profiles served as input for the wake transport and decay model P2P. P2P predicts probabilistic wake vortex behavior as a function of aircraft and environmental parameters in real time. Probabilistic components account for deviations from deterministic vortex behavior inherently caused by the stochastic nature of turbulence and vortex instabilities as well as uncertainties of environmental and aircraft parameters.

Gerz, T.

"TRAILING WAKE VORTICES IN THE ATMOSPHERE"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

The lecture focuses on the evolution of wake vortices in typical atmospheric environments. Most prominent weather factors for wake transport and decay are the runway-crossing wind, turbulence, wind shear, thermal stratification, and contact with ground. The impact of weather on the wake evolution is illustrated with examples of wake vortices in a convectively driven (i.e. thermally unstable) atmospheric boundary layer, in thermally stable and quiet air, and in wind shear flows (low-level jets). The most important finding is that the circulation decays in two phases, the slow turbulent diffusion phase (inherent to the vortices themselves) followed by a phase of rapid decay (triggered by atmospheric disturbances). At the onset of rapid decay, the second vorticity, which is produced by baroclinic forces or enhanced by stretching of turbulent eddies, is strong enough to exchange vorticity between the 2 main vortices. The wake vortex prediction and measurement campaign WakeOP in April and June 2001 at Oberpfaffenhofen, Germany, is introduced where, to the first time, a fully equipped wake vortex prediction and monitoring system has been employed. During the over-flights of a DLR research aircraft its vortices have been traced with three continuous-wave Doppler lidars to obtain correct trajectories and circulation values.

Gerz, T.

"WAKE VORTEX PREDICTION AND OBSERVATION: TOWARDS AN OPERATIONAL SYSTEM"

Proceedings 3rd ONERA-DLR Aerospace Symposium, Paris, France, June 2001, pp. S1-3/1-10

New wake-vortex related staggering procedures for approaching aircraft are sought which reduce the current separations and thereby relax airport capacity shortages but do not lower today's safety levels. Reduced aircraft separation distances seem feasible under most meteorological conditions, whilst keeping or even increasing the safety level. The paper summarizes the impact of the atmosphere on the wake vortex behavior and decay. It describes requirements of reduced separation systems and notes the properties of the systems which are currently under development or run under test

conditions. The wake forecasting and measuring campaign WakeOP is introduced which has been accomplished recently. During that campaign the trajectories and decay of the wake vortices of a particular aircraft flying with prescribed configurations have been predicted and measured under various meteorological conditions.

Gerz, T.

"WAKE VORTEX PREDICTION AND OBSERVATION IN THE ATMOSPHERE"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

DLR launched the project 'Wirbelschleppe' (German for wake vortex) to reduce the capacity bottlenecks at airports caused by wake vortex problems. The key feature of this development is a system that makes it possible to predict and observe aircraft wake vortices along the glideslopes of airports. Reduced aircraft separation distances seem feasible under most meteorological conditions, whilst keeping or even increasing the safety level. The starting point for this work is a precise understanding of the laws under which these vortices are created and decay. Numeric simulations of the flow fields behind aircraft show that wake vortices behave in different ways. How long they remain in the air and where they drift to depend on atmospheric conditions as well as the condition of the ground. Therefore, an effective prevention system will have to consist of two elements: a short-term, weather and wake forecast is necessary for the time and place of landing. In addition, the system will need to monitor the weather and the wakes and recognize particularly dangerous situations. This kind of concept would make it possible to adapt the landing distances to the weather conditions. The paper presents results from the recent wake forecasting and measuring campaign WakeOP. During that campaign the trajectories and decay of the wake vortices of a particular aircraft flying with prescribed configurations have been predicted and measured under various meteorological conditions. High resolution weather forecasting and wake predictions are operationally possible in real-time.

Gerz, T. and Baumann, R.

"DECAY CHARACTERISTICS OF SINGLE AND DOUBLE WAKE-VORTEX PAIRS IN DIFFERENT ATMOSPHERIC FLOW REALISATIONS"

ICAS 2006, Sept. 2006, Hamburg, Germany.

This study analyses the decay characteristics of aircraft wake vortices as observed in real atmospheric environments. It further assesses the capability and robustness of different wake topologies to trigger quick vortex decays in the atmosphere which, in turn, might alleviate the impact upon encountering aircraft. The analysis focuses on single and double vortex pairs and is based on data from lidar and numerical large-eddy simulations.

Gerz, T. and Ehret, T.

"WAKE DYNAMICS AND EXHAUST DISTRIBUTION BEHIND CRUISING AIRCRAFT"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 35-1 to 35-12

By means of a vortex-filament technique and large-eddy simulations dynamics are discussed which control the distribution of the exhaust of a subsonic aircraft under cruising conditions from the nozzle exit to the distance where the trailing vortex pair starts to collapse into turbulence. Emphasis is first put on the method; second on the initial roll-up process and the phenomenon of 'non-entrainment' of exhaust into the vortex cores. Third, the role of turbulence on the onset of the wingtip-vortex decay is considered; thereby it is distinguished between background atmospheric turbulence and turbulence stemming from the boundary-layer around the aircraft.

Gerz, T. and Ehret, T.

"WINGTIP VORTICES AND EXHAUST JETS DURING THE JET REGIME OF AIRCRAFT WAKES"

Aerospace Science and Tech., Vol. 1, No. 7, January 1997, pp. 463-474

By means of a vortex-filament technique and large-eddy simulations, the dynamics during the jet regime of the wake of a subsonic aircraft cruising in a stably stratified and turbulent atmosphere is simulated. Such issues as the roll-up process of the vortex sheet around the wings into the wingtip vortices, the effect of the vortices upon the deformation and displacement of the exhaust jets, and the resulting distribution of the exhaust, are addressed. It is found that the roll-up process already significantly displaces the exhaust jets. The evolving wingtip vortices attract the exhaust and collect it around the vortex cores. This entrainment is further controlled by the buoyancy force of the hot exhaust, whereas the body of the aircraft, as a source of circulation disturbance, has no significant influence. Histories of temperature and species concentration can be used to determine the duration of the jet regime which, for a cruising B-747 aircraft lasts for 20 +/- 2 s. During that time the temperature of the trapped exhaust decays to the ambient value, and then rises again. Likewise, the exhaust concentration drops to 0.03 percent of its initial value but then stays constant during the vortex regime. Throughout the jet regime, the species are inhomogeneously mixed around the vortex cores with half-moon shaped local maxima.

Gerz, T. and Holzaepfel, F.

"THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS, DESIGN AND PERFORMANCE AT FRANKFURT AIRPORT"

ODAS 2008 9th Onera-DLR Aerospace Symposium, Oct. 2008, Chatillon, France, pp. 1-19.

The design and performance of the Wake Vortex Prediction and Monitoring System WSVBS are described. The WSVBS has been developed to tactically increase airport capacity for approach and landing on closely-spaced parallel runways. It is thought to dynamically adjust aircraft separations dependent on weather conditions and the resulting wake vortex behavior without compromising

safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behavior and respective safety areas. As a safety net a LIDAR monitors the correctness of WSVBS predictions in the most critical gates at low altitude. The WSVBS is integrated in the arrival manager AMAN of DLR. Within 66 days of performance test at Frankfurt airport it was found that the system ran stable and the predicted minimum separation times were correct. The capacity improving concepts of operation could have been used in 75% of the time. From fast-time simulations the eventual capacity gain for Frankfurt was estimated to be 3% considering the real traffic mix and operational constraints in the period of one month.

Gerz, T. and Holzaepfel, F.

"WINGTIP VORTICES, TURBULENCE, AND THE DISTRIBUTION OF EMISSIONS"

AIAA Journal, Vol. 37, No. 10, 1999, pp. 1270-127.

By means of large-eddy simulations the decay of wingtip vortices and the distribution of the turbine exhaust under the influence of turbulence in a stratified atmosphere is discussed. It is distinguished between atmospheric turbulence and a random turbulent flow originating from the boundary-layer around the aircraft. The ambient turbulence is weak, anisotropic, and decaying with sizes of the most energetic eddies at the order of the separation between the two wingtip vortices. The boundary-layer turbulence is wrapped around the vortices with the maximum intensity at the core diameter. The atmospheric eddies disturb the parallel vortex tubes by advection. Once distorted at that scale, the vortex- induced velocities amplify the disturbance according to Crow's instability. The vortex tubes break up after about 1.5 minutes and form rings; the continuous trail of exhaust is reorganized in a row of single puffs. Without any atmospheric turbulence, the wake does not experience a sinusoidal instability but the parallel vortex tubes approach and start to dissolve after 2 minutes when they touch. The dissolution is triggered by the small-scale turbulent friction owing to the boundary-layer turbulence of the aircraft. The exhaust trail remains aligned along the flight track. The numerical data are compared to in-situ measurements.

Gerz, T. and Holzaepfel, F.

"WINGTIP VORTICES, TURBULENCE, AND THE DISTRIBUTION OF EMISSIONS"

AIAA Paper No. 1998-2856, June 1998, Albuquerque, NM.

By means of large-eddy simulations the decay of wingtip vortices and the distribution of the turbine exhaust under the influence of turbulence in a stratified atmosphere is discussed. It is distinguished between atmospheric turbulence and a random turbulent flow originating from the boundary-layer around the aircraft. The ambient turbulence is weak, anisotropic, and decaying with sizes of the most energetic eddies at the order of the separation between the two wingtip vortices. The boundary-layer turbulence is wrapped around the vortices with the maximum intensity at the core diameter. The atmospheric eddies disturb the parallel vortex tubes by advection. Once distorted at that scale, the vortex induced velocities amplify the disturbance according to Crow's instability. The vortex tubes break

up after about 1.5 minutes and form rings; the continuous trail of exhaust is reorganized in a row of single puffs. Without any atmospheric turbulence, the wake does not experience a sinusoidal instability but the parallel vortex tubes approach and start to dissolve after 2 minutes when they touch. The dissolution is triggered by the small-scale turbulent friction owing to the boundary-layer turbulence of the aircraft. The exhaust trail remains aligned along the flight track. The numerical data are compared to in-situ measurements.

Gerz, T. and Holzaepfel, F.

"AIRCRAFT WAKE VORTICES IN THE ATMOSPHERE"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 169-184

By means of large-eddy simulations dynamics are discussed which control the decay of the wake vortices of a subsonic aircraft under cruising conditions. The period between 1 second and several minutes of wake age is considered. The method is briefly introduced. Emphasis is put on the effect of turbulence on the decay process of the wingtip vortices; thereby it is distinguished between background atmospheric turbulence and turbulence stemming from the boundary layer of the aircraft. Some results of wake vortices measured during flight campaigns as well as results of large-eddy simulations of the convective atmospheric boundary layer are presented.

Gerz, T. and Holzaepfel, F.

"LES OF WAKE VORTICES IN A STRATIFIED AND TURBULENT ATMOSPHERE"

Proceedings of the International Wake Vortices Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 69-72

Results of large-eddy simulations (LES) of the wake flow induced by a large-bodied aircraft flying through a stably stratified and turbulent atmosphere are presented. Details of the dynamics in the Jet, Vortex, and Dispersion regimes are outlined and analyzed. In a stratified and weakly turbulent atmosphere, as typical at cruising altitudes, the organized wingtip vortices collapse in the period between 1.5 and 3 minutes. The vortices live about 3 minutes when small-scale intense turbulent friction from the boundary-layer turbulence of the aircraft erodes them slowly. The vortices start to break up after 1.5 minutes already when weak atmospheric eddies of the size of the wing span trigger a large-scale oscillatory (Crow) instability. More intense atmospheric turbulence, typical for the lowest 2 km of the atmosphere, destroys the vortices even earlier by direct interaction between the eddies and the vortices. For weak to moderate stratification the baroclinic torque at the vortex boundaries detains mass, thus leading to a decreasing distance between the vortex centers which, in turn, accelerates the flow. For strong stratification it is observed that the vortices first decelerate and then vigorously accelerate their descent.

Gerz, T. and Palma, J.

"INFLUENCE OF ATMOSPHERIC TURBULENCE ON THE DEVELOPMENT OF AN IDEALIZED AIRPLANE WAKE: NUMERICAL STUDIES"

Impact of Emissions from Aircraft and Spacecraft Upon the Atmosphere, edited by U. Schumann and D. Wurzel, DLR-Mitteilung 94-06, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt, Köln, Germany, 1994, pp. 309-314

The effect of a turbulent, sheared, and stably stratified atmosphere on the wake behind a cruising aircraft is studied by means of Direct Numerical Simulation. An early and a late evolutionary stage of the wake are considered. In the early stage, the flow consists of a developed pair of trailing vortices of the Rankine type; the late stage is after collapse of the organized vortex pair leaving a patch of enhanced turbulence behind in the otherwise calm atmosphere. As a preliminary result it is found that atmospheric turbulence mixes efficiently (within seconds) at scales smaller than the vortex-core diameter. Consequently, the in-core pressure increases and trapped substances are released.

Gerz, T. and Schwarz, C. (editors)

"THE DLR PROJECT WETTER AND FLIEGEN (WEATHER AND FLYING)"

Forschungsbericht 2012-02, 2012, DLR Research Centers Oberpfaffenhofen, Braunschweig, Göttingen and Hamburg, Germany.

This report compiles major results of the 4-year DLR Project Wetter and Fliegen. Contributing DLR institutes and facilities were the Institutes of Atmospheric Physics, Flight Systems, Flight Guidance, Robotics and Mechatronics, Aerodynamics and Flow Technology, Air Transportation Systems as well as DLR Flight Experiments and Systemhaus Technik. The aim was to contribute to safety and efficiency of tomorrow's air transportation by developing weather and wake vortex expert systems along with operational concepts for the air traffic management and control at airports and researching new sensors and delivering automated flight control and innovative flight crew information technologies for the aircraft. Deeper insights were gained into wake vortex physics, the consequences for wake-encountering aircraft and separation prediction, as well as the detection, tracking and prediction of adverse weather phenomena like thunderstorms and snow and icing conditions. New operational concepts for air traffic control and tools for flight systems have been developed and the expert systems have been assessed from a technological and economical perspective. Prototype systems have been matured towards different levels of technological readiness and have been tested and evaluated with human-in-the-loop simulations and in field campaigns in real environments. Building on these achievements the work will be continued in the forthcoming DLR Project Weather Optimized Air Traffic.

Gerz, T., Durbeck, T. and Konopka, P.

"TRANSPORT AND EFFECTIVE DIFFUSION OF AIRCRAFT EMISSIONS"

Journal of Geophysical Research D: Atmospheres, Vol. 103, Issue D20, 1998, pp. 25905-25913

The transport and effective diffusion of exhaust are analyzed in the wake flow of a large-bodied aircraft which flies through a stably stratified, sheared, and turbulent atmosphere. The analysis is based on data sets from large-eddy simulations of the wake in the atmosphere. Diffusion and dilution measures are obtained from a chemically inert species concentration. Most of the exhaust is concentrated and isolated in the two wing tip vortices (the 'primary wake'). However, as the vortices sink through a stably stratified atmosphere, a baroclinic torque develops between the vortices and the surrounding flow and detrains about 10 to 30% of the exhaust mass from the vortices into the ambient air (the well mixed 'secondary wake'). Consequently, the entrainment rates computed for the primary and secondary wakes differ by orders of magnitude. In the period between 1.5 and 3 min the vortices collapse into aircraft turbulence. The trapped emissions of the primary wake are now released and diffused by ambient turbulence and shear. After about 5 min the exhaust concentration has been diluted by 0.00002 and 0.00004 compared to the value at the nozzle exit for the primary and secondary wakes, respectively, and covers areas of about 50,000 m squared and 20,000 m squared. Under flow conditions typically found at cruising heights the emissions are diluted to background concentrations within 2 and 12 hours for wind shear between 0.002 and 0.01/s. The spatial plume extension does not exceed the lower mesoscale range (20 km horizontally and 0.3 km vertically). Good to excellent agreement is achieved between the numerical results and in situ measured data.

Gerz, T., Frech, M., Hahn, K.-U., Holzaepfel, F., Kopp, F., Schwarz, I. and Tafferner, A.

"ATMOSPHERIC IMPACT ON WAKE VORTEX DEVELOPMENT"

European Congress on Computational Methods in Applied Sciences and Engineering, ECCOMAS 2004, edited by Neittaanm, Rossi, Korotov, Odate, Periaux and Knorzer, July 2004, Jyvaskyla, Finland.

Wake turbulence is one of the main reasons for capacity problems at busy airports. Solutions for new aircraft staggering procedures are sought which relax the current separations but do not lower today's safety levels. It is hoped that wake vortex warning systems will contribute to such a solution. For setting up a wake vortex warning system, the knowledge of wake vortex behavior under varying meteorological conditions achieves utmost significance. This paper will illustrate the impact of atmospheric parameters on the transport and decay of trailing wake vortices shed by commercial aircraft. Moreover, the architecture and design of a wake vortex prediction and monitoring system for busy airports will be outlined. Finally, two wake-vortex measurement and prediction campaigns will be described where the major components of that system have been tested successfully.

Gerz, T., Frech, M., Tafferner, A., Birke, L., Kopp, F. and Holzaepfel, F.

"EUROPEAN PREDICTION AND MEASUREMENT CAMPAIGNS OF WAKE VORTICES AND METEOROLOGICAL PARAMETERS: DATASETS, QUALITY ASSESSMENT AND ACHIEVEMENTS"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

This talk highlighted the major outcomes of recent wake vortex campaigns in terms of forecasted and observed meteorological conditions and their impact on predicted and measured wake vortex transport and decay. The necessity of probabilistic approaches will be pronounced. The potential to reduce aircraft separations with the given quality of prediction and observation data and methods will be discussed.

Gerz, T., Holzaepfel, F. and Darracq, D.

"COMMERCIAL AIRCRAFT WAKE VORTICES"

Progress in Aerospace Sciences, Vol. 38, 2002, pp. 181-208

The paper discusses the problem of aircraft wake vortices. It presents a consolidated European view on the status of knowledge of the nature and characteristics of aircraft wakes and of technical and operational procedures of minimizing and predicting the vortex strength and avoiding wake encounters. Methodological aspects of data evaluation and interpretation, like the description of wake ages, the characterization of wake vortices, and the proper evaluation of wake data from measurement and simulation, are addressed in the first part. In the second part, an inventory of our knowledge is given on vortex characterization and control, prediction and monitoring of vortex decay, vortex detection and warning, vortex encounter models, and wake vortex safety assessment. Each section is concluded by a list of questions and required actions which may help to guide further research activities.

Gerz, T., Holzaepfel, F. and Stephan, A.

"AIRCRAFT WAKE VORTICES IN THE ATMOSPHERIC BOUNDARY LAYER"

18th Conference on Aviation, Range, and Aerospace Meteorology, January 2017, Seattle, WA.

This paper introduces wall-resolved large eddy simulations to investigate the behavior of wake vortices in ground proximity at a variety of wind conditions. The six considered strengths of wind, ranging between 0.5 and 4 times the initial wake vortex descent speed, w , include practically and theoretically significant wind speeds. A crosswind of $0.5w$ may lead to windward stall posing a potential hazard to subsequently landing aircraft, whereas theoretical considerations predict that at $4w$ the rebound of the luff vortex is completely suppressed. The same range of wind speeds is also used to investigate the effects of headwind and diagonal wind to discriminate between effects of environmental turbulence increasing with wind speed and the direction of the wind shear. It is shown that vortex ascent, descent, rebound and decay characteristics are controlled by (i) the interaction of the vortices with secondary vorticity detaching from the ground, (ii) the redistribution of vorticity of the boundary layer which is altering the path of the primary vortices by mutual velocity induction, and (iii) the interaction of the vortices with the environmental turbulence.

Gerz, T., Holzaepfel, F., Bryant, W., Kopp, F., Frech, M., Tafferner, A. and Winckelmans, G.

"RESEARCH TOWARDS A WAKE-VORTEX ADVISORY SYSTEM FOR OPTIMAL AIRCRAFT SPACING"

C. R. Physique, Vol. 6, 2005, pp. 501-523

Wake turbulence is a major concern for busy airports since it limits capacity. Solutions for new aircraft staggering procedures are sought which relax the current separations but keep safety on a high level. Systems which advise air-traffic control on wake-vortex behavior under present and expected weather conditions will, hopefully, contribute to such a solution. Knowledge on transport and decay of wake vortices in the atmosphere is presented. Concepts and designs of wake-vortex advisory systems in Europe and the USA are outlined. European wake-vortex measurement and prediction campaigns are described where the components of such systems have been tested successfully.

Gerz, T., Holzaepfel, F., Frech, M., Tafferner, A., Birke, L., Schwarz, C., Hahn, K.-U. and Joos, D.

"POSSIBLE CAPACITY GAINS FOR A GENERIC AIRPORT USING DLR'S WAKE VORTEX PREDICTION AND MONITORING SYSTEM"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

We will present results of various studies on possible capacity gains for a generic and for Frankfurt airport when using a WVPMS (wake vortex predicting and monitoring system). We developed a WVPMS within DLR's project Wirbelschleppe and the EU-project ATC-Wake. Data from the measurement and forecasting campaigns in C-Wake (WakeOP, WakeTOUL) and AWIATOR as well as from the Memphis and Dallas-Fort Worth campaigns in the USA have been utilized to demonstrate the impact of forecasted and observed meteorological properties on minimum safe aircraft separations. It is shown that prediction and measurement of the runway-crossing component of the horizontal wind vector bears a robust potential to apply minimum aircraft separations at a generic single-runway airport. Moreover, for Frankfurt airport a preliminary study on the potential for reduced separations on single and parallel runways is presented. The results are based on four days of weather data predicted by NOWVIV, vortex evolution predicted by P2P (i.e., the forecasting part of the WVPMS) and simplifying assumptions for aircraft adherence to the glide path and potentially hazardous areas around vortex centers. We will close our presentation by illuminating the skills of local weather forecasting techniques today and tomorrow and their impact on improved wake vortex predictions as well as on an increase in punctuality of air transportation in general.

Gerz, T., Holzaepfel, F., Gerling, W., Scharnweber, A., Frech, M., Kober, K., Dengler, K. and Rahm, S.

"THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS PART II: PERFORMANCE AND ATC INTEGRATION AT FRANKFURT AIRPORT"

Air Traffic Control Quarterly, Vol. 17, No. 4, 2009, pp. 323-346.

The performance and the ATC test integration of DLR's wake vortex advisory system, WSVBS, for the dependent parallel runways 25L and 25R at Frankfurt Airport are described. WSVBS has components to

forecast and monitor the local weather and to predict and monitor wake transport and decay along the glide paths. Integration with the DLR's arrival manager AMAN has also been demonstrated. Every 10 minutes the WSVBS delivers minimum safe aircraft separation times for the next hour, which are translated into operational modes for runways 25L/R aiming at tactically improving capacity to reduce delays. During a performance test described herein the system was stable and the predicted minimum separation times were confirmed by measurements. Capacity-improving wake-vortex separation concepts of operation could have been applied used in 75% of the time and continuously applied for at least several tens of minutes. From fast-time simulations the (strategic) capacity gain for Frankfurt was estimated to be 3%, considering the real traffic mix and operational constraints.

Gerz, T., Holzaepfel, F., Gerling, W., Scharnweber, A., Frech, M., Kober, K., Dengler, K. and Rahm, S.

"THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS PART II: PERFORMANCE AND ATC INTEGRATION AT FRANKFURT AIRPORT"

Air Traffic Control Quarterly, Vol. 17, No. 4, pp. 323-346.

The performance and the ATC test integration of DLR's wake vortex advisory system, WSVBS, for the dependent parallel runways 25L and 25R at Frankfurt Airport are described. WSVBS has components to forecast and monitor the local weather and to predict and monitor wake transport and decay along the glide paths. Integration with the DLR's arrival manager AMAN has also been demonstrated. Every 10 minutes the WSVBS delivers minimum safe aircraft separation times for the next hour, which are translated into operational modes for runways 25L/R aiming at tactically improving capacity to reduce delays. During a performance test described herein the system was stable and the predicted minimum separation times were confirmed by measurements. Capacity-improving wake-vortex separation concepts of operation could have been used in 75 percent of the time and continuously applied for at least several tens of minutes.

Gerz, T., Holzaepfel, F., Gerling, W., Scharnweber, A., Frech, M., Wiegele, A., Kober, K., Dengler, K. and Rahm, S.

"THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS PART II: PERFORMANCE AND ATC INTEGRATION AT FRANKFURT AIRPORT"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-178, September 2007, pp. 3391-3399.

The performance and ATC integration of DLR's wake vortex advisory system 'WSVBS' (Wirbelschleppen-Vorhersage- and -Beobachtungssystem) for the dependent parallel runway system 25L and 25R at Frankfurt Airport are described. WSVBS has components to forecast and monitor the local weather and to predict and monitor wake transport and decay along the glide paths. WSVBS is integrated in the arrival manager AMAN of DLR. Each 10 minutes it delivers minimum safe aircraft separation times for the next hour to air traffic control. These times are translated into operational modes for runways 25L/R aiming at improving the capacity. From 66 days of a performance test at

Frankfurt it was found that the system ran stable, the predicted minimum separation times were safe and the capacity improving concepts of operation could be used in 75% of the time. From the fast-time simulations the eventual capacity gain for Frankfurt was estimated to be 3% considering the real traffic mix and operational constraints in the period of one month.

Gerz, T., Holzaepfel, F., Hofbauer, T., Dornbrack, A. and Frech, M.

"AIRCRAFT WAKE VORTICES IN THE ATMOSPHERE"

Industrial and Environmental Applications of Direct and Large-Eddy Simulation, Lecture Notes in Physics, Vol. 529, Springer Verlag, 1999, pp. 83-92.

The studies summarized here were motivated by the need to gain information (i) about the impact of aircraft emissions upon the atmosphere and the climate and (ii) about optimized separation distances between aircraft landing at an airport for possibly increasing its capacity. To this end, large-eddy simulations have been performed to learn about the behavior of vortex wakes shed by cruising aircraft in the free atmosphere and in the atmospheric boundary layer close to the ground.

Gesich, W. E.

"THE DOWNWASH DISTRIBUTION BEHIND A WING WITH AN ANGLE OF ATTACK DISCONTINUITY AT SUPERSONIC SPEEDS"

Degree of Aeronautical Engineer, June 1948, California Institute of Technology, Pasadena, CA.

Investigation of the downwash field behind a wing with an angle of attack discontinuity at supersonic speeds by use of linearized conical flow theory has shown the downwash to be of finite magnitude at all points in and behind the plane of the wing. The downwash at more than five chord lengths behind the wing was found to asymptotically approach the value of downwash calculated in the Trefftz plane. Behind the wing and within the span that is determined by the intersection of the Mach cones from the leading edge with the trailing edge, an inexplicable action of the downwash was found to exist. It was found that at the trailing edge the downwash was a 100 percent of that on the wing surface. At two chord lengths, the downwash was 83 percent. Upon moving aft, it was found that the downwash increased in magnitude and that at 10 chord lengths, it asymptotically approached the value at the Trefftz plane, namely 100 percent again. By considering an idealized missile configuration, it was found that roll reversal was possible. The possibility of reversal was found to be almost entirely dependent upon the location of the control lifting surfaces with respect to one another..

Gessow, A.

"AIRCRAFT WAKE TURBULENCE MINIMIZATION BY AERODYNAMIC MEANS"

Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorology Society, 1974

The paper reviews NASA's efforts on wake vortex turbulence minimization by aerodynamic design or retrofit modifications to large transport aircraft. Theoretical and experimental (ground-based and flight) results are presented which show that the adverse effects of a vortex wake produced by a large aircraft on a small following aircraft can be reduced significantly.

Geurts, B. J. and Kuczaj, A. K.

"WAKE-VORTEX DECAY IN EXTERNAL TURBULENCE"

ERCOFTAC Workshop, Direct and Large Eddy Simulation VII, September 2008, Trieste, Italy, pp. 513-518.

In this paper we considered the role of external turbulence in the decay of two counter-rotating vortices. At sufficiently high turbulence levels the decay of kinetic energy was found to be strongly increased. Particularly, the large scales are considerably reduced, hence constituting an interesting option for future aircraft separation under sufficiently lively meteorological conditions. The prediction of the vortical decay with LES based on regularization modeling was shown to yield accurate capturing of the velocity skewness and the Taylor Reynolds number. The parametric study documenting the precise influence of external turbulence on vortical decay at realistic Reynolds numbers is subject of ongoing research.

Geyer, M., Soares, M., Barnes, S., Hoff, A. and Mackey, S.

"RNAV (GPS) TOTAL SYSTEM ERROR MODELS FOR USE IN WAKE ENCOUNTER RISK ANALYSIS OF DEPENDENT PAIRED APPROACHES TO CLOSELY-SPACED PARALLEL RUNWAYS"

DOT-VNTSC-FAA-14-05, February 2014, Volpe National Transportation Systems Center, Cambridge, MA.

The purpose of this memorandum is to provide recommended Total System Error (TSE) models for aircraft using RNAV (GPS) guidance when analyzing the wake encounter risk of proposed simultaneous dependent ('paired') approach operations to Closely Spaced Parallel Runways (CSPR, defined as having centerline spacing less than 2,500 feet). RNAV (GPS) is being evaluated as a source of guidance to aircraft approaching one or both runways of specific CSPR pairs, in lieu of or in addition to ILS guidance, for possible inclusion in future changes to FAA Order 7110.308 and/or in future orders authorizing Wake Turbulence Mitigation for Arrivals -- Procedure-based (WTMA-P).

Ghalebssaz-Jeddi, B., Donohue, G. L. and Shortle, J. F.

"A STATISTICAL ANALYSIS OF THE AIRCRAFT LANDING PROCESS"

Journal of Industrial and Systems Engineering, Vol. 3, No. 3, 2009, pp. 152-169.

Managing operations of the aircraft approach process and analyzing runway landing capacity, utilization and related risks require detailed insight into the stochastic characteristics of the process. These characteristics can be represented by probability distributions. The focus of this study is analyzing landings on a runway operating independent of other runways making it as a single runway. We provide statistical analysis of the final approach and runway occupancy time at Detroit airport at peak traffic periods on one of its major landing runways. Many weeks of aircraft track record data collected by a multilateration surveillance system is analyzed. We explain some characteristics and short comings of the database, and extract samples of the random variables of interest (i.e. aircraft time and distance separation, runway occupancy time, simultaneous runway occupancy, and aircraft speed). We estimate probability distributions of these variables under both instrument and visual flight rules. Although the focus here is on one runway at a large airport, probability distributions of these random variables for the landings on similar single or independent runways (with similar physical design, operating systems and landing guidance instruments) shall be alike.

Gharakhani, A.

"A LAGRANGIAN VORTEX METHOD FOR GRID-FREE DYNAMIC LES"

AIAA Paper 2005-4625, June 2005, Toronto, Canada.

A vorticity-based method for the Large Eddy Simulation (LES) of inhomogeneous turbulent incompressible flow is presented. To this end, the dynamics of the resolved vorticity field are accounted for via a grid-free Lagrangian Vortex Element Method. Turbulence is modeled using a Lagrangian dynamic Smagorinsky Sub-Grid-Scale (SGS) model. The latter is a grid-free, particle-based adaptation of the Lagrangian dynamic model that was originally developed for the primitive variable formulation of the Navier-Stokes equations, and applied successfully to grid-based simulations of inhomogeneous turbulent flow. In this paper, the formulations and basic concepts associated with incorporating the dynamic LES model in the Vortex Element Method are outlined. In addition, the salient features of the grid-free model are demonstrated using preliminary results from the very early stages of jet flow into a quiescent environment at Reynolds number 4,000 based on the jet diameter and inlet velocity.

Gharakhani, A. and Stock, M. J.

"3-D VORTEX SIMULATION OF FLOW OVER A CIRCULAR DISK AT AN ANGLE OF ATTACK"

AIAA Paper 2005-4624, June 2005, Toronto, Canada.

A Lagrangian Vortex Method for grid free simulation of unsteady incompressible laminar flow over 3-D geometries is developed. To this end, the fluid velocity is discretized using singular vortex particles and its inviscid transport predicted in a Lagrangian frame of reference using smooth velocity and velocity gradients. Diffusion is accounted for via the application of a Vorticity Redistribution Method, which facilitates automatic insertion of new vortex particles as vorticity spreads out due to diffusion. The object boundaries are discretized with triangular panels, and the wall velocity boundary conditions

imposed by solving a Petrov-Galerkin discretization of the Fredholm boundary integral equation of the second kind for the vector-valued sheets at the wall. A parallel adaptive oct-tree code is used to accelerate the velocity (and gradient) evaluations due to the vortex particles and panels. This paper describes the developed algorithm briefly and presents results from the simulation of impulsively started flow over a circular discoid, with thickness equal to a tenth of its diameter and positioned at a 30-degree angle of attack. The Reynolds number based on the freestream velocity and the discoid diameter is 1,000 for this problem.

Ghazi, M. A. and Olwi, I. A.

"INTERFERENCE EFFECTS OF A LARGE WING ON THE PERFORMANCE OF A TRAILING WING"

Journal of King Saud University, Vol. 7, 1995, pp. 77-92.

Interference of trailing vortices from a flapped large leading wing on a flapped small trailing wing is experimentally investigated. The effect of such wake turbulence is investigated through wind tunnel measurements of lift and drag forces and the pitching moment on the trailing wing. The threat of wake vortices was manifested in substantial reduction in the lift performance. Such reduction of lift was magnified as the leading wing flap angle increased, but without affecting the slope of the lift coefficient curves. The resulting shift of those curves resulted in delayed separation on the trailing wing to higher angles of attack. Within the domain of parameters used in the study, the trailing wing stall angle has roughly doubled when a large wing equipped with a 30-degree flap was placed in the leading position. The drag force had been reduced as the leading wing flap angle was increased. However, the trailing wing stability had not been harassed by such hazard.

Ghee, T. A. and Elliott, J. W.

"THE WAKE OF A SMALL-SCALE ROTOR IN FORWARD FLIGHT USING FLOW VISUALIZATION"

Journal of the American Helicopter Society, Vol. 40, No. 3, July 1995, pp. 52-65.

An experimental investigation was conducted in the 14- by 22-Foot Subsonic Tunnel at NASA Langley Research Center to quantify the rotor wake behind a scale model helicopter rotor in forward flight at one thrust level. The rotor system used in the present test consisted of a four-bladed, fully articulated hub and utilized blades of rectangular planform with a NACA-0012 airfoil section. A laser light sheet, seeded with propylene glycol smoke, was used to visualize the flow in planes parallel and perpendicular to the freestream flow. Quantitative measurements of vortex location, vertical skew angle, and vortex particle void radius were obtained for vortices in the flow; convective velocities were obtained for blade tip vortices. Comparisons were made between the experimental results and the wake geometry generated by computational predictions. The results of these comparisons show that the interaction between wake vortex structures is an important consideration for correctly predicting the wake geometry.

Ghee, T. A., Berry, J. D., Zorri, A. J. and Elliott, J. W.

"WAKE GEOMETRY MEASUREMENTS AND ANALYTICAL CALCULATIONS ON A SMALL-SCALE ROTOR MODEL"

NASA TP-3584, August 1996, NASA Langley Research Center, Hampton, VA

An experimental investigation was conducted in the Langley 14- by 22-Foot Subsonic Tunnel to quantify the rotor wake behind a scale model helicopter rotor in forward level flight at one thrust level. The rotor system in this test consisted of a four-bladed fully articulated hub with blades of rectangular planform and an NACA 0012 airfoil section. A laser light sheet, seeded with propylene glycol smoke, was used to visualize the vortex geometry in the flow in planes parallel and perpendicular to the free-stream flow. Quantitative measurements of wake geometric properties, such as vortex location, vertical skew angle, and vortex particle void radius, were obtained as well as convective velocities for blade tip vortices. Comparisons were made between experimental data and four computational method predictions of experimental tip vortex locations, vortex vertical skew angles, and wake geometries. The results of these comparisons highlight difficulties of accurate wake geometry predictions.

Ghias, R., Mittal, R., Dong, H. and Lund, T. S.

"STUDY OF TIP-VORTEX FORMATION USING LARGE-EDDY SIMULATION"

AIAA Paper No. 2005-1280, Reno, NV, January 2005

The formation of the tip-vortex from a rectangular NACA 2415 wing-tip at a chord Reynolds number of 10000 has been simulated. The simulations employ a parallelized compressible large-eddy simulation solver that has been developed to simulate wing and rotor tip-flows. The solver employs an immersed-boundary technique in conjunction with a curvilinear structured grid and the dynamic model is used to model the subgrid-scale stress terms. A detailed discussion of the tip-vortex formation and evolution in the near wake is presented.

Ghias, R., Mittal, R., Dong, H. and Lund, T. S.

"LARGE-EDDY SIMULATION OF THE TIP FLOW OF A ROTOR IN HOVER"

AIAA Paper No. 2004-2432, Portland, OR, June-July 2004

An efficient and flexible parallel version of a Large-Eddy Simulation (LES) solver has been developed to simulate the compressible tip-flow of a rotor in hover. The solver employs an immersed-boundary technique in conjunction with a curvilinear structured grid and the dynamic model is used to model the sub-grid scale (SGS) stress terms. The solver also employs a hybrid implicit-explicit time-discretization scheme wherein the diagonal viscous terms are treated implicitly and all other terms including the convective terms and cross-terms are treated explicitly using a low-storage third-order Runge-Kutta

scheme. A mixed second-order central-difference-QUICK scheme has been used which allows us to precisely control the numerical damping. Preliminary results from non-rotating tip-flow are presented.

Ghigliazza, H. H., Martinez-Val, R. and Perez, E.

"FLYING WING TRAILING VORTICES, REDUCING A TECHNOLOGICAL HAZARD"

Third LACCEI International Latin American and Caribbean Conference for Engineering and Technology, June 2005, Cartagena, Columbia.

The flying wing is being studied as one of the future promising concepts that could alleviate some problems of the air transportation system, for exhibiting better aerodynamics and reduction of fuel burn, pollution and noise than conventional aircraft; and for flying in unused flight levels. Hence, this configuration is receiving a great deal of attention from various perspectives: performance and control; passenger acceptance and evacuation; airport compatibility; etc. This paper addresses the problem of trailing vortices shed from the flying wing. All airplanes, in any part of the flight, produce an intense wake mainly characterized by a pair of counter-rotating vortices, originated at the wing tips. The wake thus formed is very severe, with induced velocities higher than those found in natural atmospheric turbulence, although it decays further downstream. This phenomenon obliges to maintain certain safety distances in take-off and landing maneuvers which, in its turn, imply a time-lag between subsequent operations imposing a limit on the number of movements per runway. For various reasons, in-flight encounters are rare. The present paper provides estimations of core size, induced velocities and other relevant features of the wake of the flying wing, and shows that it is far less hazardous than that of conventional aircraft of the same size.

Ghigliazza, H. H., Martinez-Val, R., Perez, E. and Smrcek, L.

"WAKE OF TRANSPORT OF FLYING WINGS"

Journal of Aircraft, Vol. 44, No. 2, March-April 2007, pp. 558-562

Flying wings are among the most promising concepts regarding the ever-increasing air traffic demand. They could help in improving economic efficiency and would be environmentally friendly, both in terms of emissions and noise. This paper addresses the problem of trailing vortices shed from the flying wing, arranged as a pair of counter-rotating vortex tubes as in conventional aircraft. The turbulence produced by the wake obliges airports to maintain certain time and distance separation between aircraft in takeoff and landing maneuvers, imposing a limit on the number of movements per runway. With the help of a simple model, the present paper provides preliminary estimations of circulation, core size, induced velocities, and other relevant features of the wake of transport flying wings and shows that it is less hazardous than that of conventional aircraft of similar size.

Ghimire, H. C. and Bailey, S. C. C.

"AN EXPERIMENTAL INVESTIGATION OF WING-TIP VORTEX DECAY IN TURBULENCE"

Physics of Fluids, Vol. 29, 2017, pp. 037108-1 to 037108-10.

Particle image velocimetry measurements were conducted for a wing-tip vortex decaying in free-stream turbulence. The vortex exhibited stochastic collapse with free-stream turbulence present, with the breakdown initiating earlier for higher levels of turbulence. An increased rate of decay of the vortex tangential velocity was also observed, increasing with increasing free-stream turbulence. The decay of the vortex tangential velocity without the free-stream turbulence was well represented by viscous diffusion, resulting in an increase in the core radius and decrease in the peak tangential velocity. With the addition of free-stream turbulence, the rate of decay of the peak tangential velocity of the vortex increases, whereas the rate of increase of core radius remains unchanged. The circulation of the vortex decayed in time when immersed in free-stream turbulence, whereas it remained approximately constant when free-stream turbulence was not present. This decay in circulation was found to be almost entirely due to a decrease in circulation of the vortex core, caused by the relative decrease in the peak tangential velocity without a corresponding increase in the core radius. The scaling of the radial profiles of velocity and circulation was also examined, and it was found that, regardless of the free-stream condition, the core was scaled by the peak tangential velocity and core radius. The region outside the core did not scale with these quantities, and an alternative scaling for circulation is proposed which results in improved collapse of the profiles.

Ghoreyshi, M., Bergeron, K. and Lofthouse, A. J.

"NUMERICAL SIMULATION OF WAKE FLOWFIELD BEHIND THE C-130H CARGO RAMP"

AIAA Paper 2016-4182, June 2016, Washington, DC.

This effort reports the development of a systems engineering capability at the U.S. Army Natick Soldier Research, Development, and Engineering Center through virtual prototyping of airdrop systems based on high performance computing. Simulation results are presented for a C-130H aircraft configured to perform cargo airdrop operations. Flight operations with either the troop door or cargo door open lead to strong vortical flow structures and unsteady flows which can adversely affect airdrop operations and parachute deployments. The turbulent flow associated with the spiral-shaped slipstream formed behind a rotating propeller, prop wash, may also disturb airdrop operations. Thus, the simulation models of this work consider propeller effects by replacing them with actuator disks. Grid and time sensitivity studies are performed for each geometry to ensure numerical simulations are accurate for the separated and vortical flows. The results reveal that complex wake structures are formed behind the C-130 with the cargo door open. In particular, the wake contains two asymmetric counter-rotating vortices formed near the rear edges of cargo storage. The flow separates along these edges because of the sharp turn that flow makes as it enters inside cargo storage. The separated flow then rolls up into two vortices. These vortices move outward and upward and then pass very near the lower surface of the horizontal tail. These vortical flows will therefore cause significant unsteady air loads on the tail and thus aircraft. The wake effects are larger behind the upper cargo storage section and are minimum at the lower positions. Finally, the results show that as the grid becomes more refined behind the cargo storage, the localized wake structures and unsteady effects are better captured by the flow solver.

Ghoreyshi, M., Bergeron, K. and Lofthouse, A. J.

"NUMERICAL SIMULATION OF WAKE FLOWFIELD BEHIND THE C-130 WITH CARGO RAMP OPEN"

Journal of Aircraft, Vol. 55, No. 3, May-June 2018, pp. 1103-1121.

Simulation results are presented for a C-130 aircraft configured to perform cargo airdrop operations. Flight operations with the cargo ramp open lead to strong vortical flow structures and unsteady flows, which can adversely affect airdrop operations and parachute deployments. The results document complex wake structures formed behind the C-130 with the cargo ramp open at 0 and 50 percent flap settings. In particular, the wake contains two asymmetric counter-rotating vortices formed between the open ramp and the upsweep section of the aircraft and near the rear edges of the ramp. The flow separates along these edges because of the sharp turn that flow makes as it enters inside cargo compartment. The separated flow then rolls up into two vortices. These vortices move outward and upward, and then they pass very near the lower surface of the horizontal stabilizer. These vortical flows lead to unsteady air loads on the horizontal stabilizer, and thus the aircraft. The wake effects are larger behind the upper upsweep section and are minimum at the lower positions. Grid and time sensitivity studies are performed for several geometries to ensure numerical simulations are accurate for the separated and vortical flows. The results show that, as the grid becomes more refined in the region behind the upsweep section of the aircraft, the localized wake structures and unsteady effects are better captured by the flow solver.

Ghosh, D. and Constantinescu, E. M.

"WELL-BALANCED, CONSERVATIVE FINITE DIFFERENCE ALGORITHM FOR ATMOSPHERIC FLOWS"

AIAA Journal, Vol. 54, No. 4, April 2016, pp. 1370-1385.

The numerical simulation of meso-, convective-, and microscale atmospheric flows requires the solution of the Euler or the Navier-Stokes equations. Nonhydrostatic weather prediction algorithms often solve the equations in terms of derived quantities such as Exner pressure and potential temperature (and are thus not conservative) and/or as perturbations to the hydrostatically balanced equilibrium state. This paper presents a well-balanced, conservative finite difference formulation for the Euler equation with a gravitational source term, where the governing equations are solved as conservation laws for mass, momentum, and energy. Preservation of the hydrostatic balance to machine precision by the discretized equations is essential because atmospheric phenomena are often small perturbations to this balance. The proposed algorithm uses the weighted essentially non-oscillatory and compact-reconstruction weighted essentially non-oscillatory schemes for spatial discretization that yields high-order accurate solutions for smooth flows and is essentially non-oscillatory across strong gradients; however, the well-balanced formulation may be used with other conservative finite difference methods. The performance of the algorithm is demonstrated on test problems as well as benchmark atmospheric flow problems, and the results are verified with those in the literature.

Ghost, S., Lohry, M. W. and Rajagopalan, R. G.

"ROTOR CONFIGURATIONAL EFFECT ON ROTORCRAFT BROWNOUT"

AIAA Paper No. 2010-4238, June-July 2010, Chicago, Illinois.

One of the major problems faced by rotorcraft undergoing aerodynamic maneuvers at low altitude in arid desert regions is in-flight visibility restriction due to the formation of dust clouds in the air. This phenomenon known as Brownout is caused by dust and sand particle entrainment into the air by the impinging downwash of the rotor. One of the various factors which influence the characterization of brownout is rotor configuration. This paper describes the analysis of rotor configurational (single-rotor, tandem-rotor, tilt-rotor, and quad-rotor) effect on ground footprint, wake and brownout using Computational Fluid Dynamics. In this study, the flow field is calculated by solving Reynolds averaged Navier-Stokes equation using the SIMPLER algorithm. To solve for turbulence properties, realizable kappa-epsilon equation is used. The rotor is modeled as momentum source whereas the dust behavior is solved using an Eulerian-based dust transport equation.

Gibbons, J. E. and Mollo-Christensen, E.

"BEHAVIOR OF A TRAILING VORTEX IN A FAVORABLE PRESSURE GRADIENT"

AIAA Journal, Vol. 1, No. 3, March 1963, pp. 705-706

The purpose of this study is the investigation of a streamwise vortex in low-turbulence channel flow, with particular attention to the high-shear region of the vortex core. Transverse-velocity profiles through the flow indicate that nearly discrete cylindrical vortex sheets are formed.

Gibbs, J.

"EXPERIMENTAL DETERMINATION OF LIFT AND LIFT DISTRIBUTIONS FOR WINGS IN FORMATION FLIGHT"

MS Thesis, January 2005, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Experimental methods for the investigation of trailing vortex strengths, total lift, and lift distributions for three-dimensional wings in close-proximity flight were developed. With these experiments we model compound aircraft flight either docked tip-to-tip, or flying in formation. There is a distinct lack of experimental formation flight data using three-dimensional wing models for tests. The absence of fixed walls on either end of the wing permits the development of the asymmetric shedding of vortices, and the determination of the asymmetric circulation distribution induced by the proximity of the leading wing. The pair consisted of a swept NACA-0012 non-cambered wing simulating one half of a leading aircraft and a rectangular cambered NACA 63-420 wing simulating the trailing aircraft. Important aspects of the work included theoretical development, experimental setup, data acquisition and processing, and results validation. Experimentally determining the lift for formation flight, in addition to

the local flow behavior for a pair of wings, can provide valuable insight for the proposition of flying actual aircraft in formation to increase mission efficiency. To eliminate the need for bulky mounting stings and direct load measurement devices that can potentially interfere with the local flow field, a minimally invasive velocity probe method is developed. A series of experiments were performed to assist with the development of the method. Velocity and vorticity distributions obtained along a near-field plane were processed to calculate wingtip vortex strengths. Additionally, vortex position instabilities and the shedding of vorticity inboard of the wingtips were observed. To determine the circulation distributions for the trailing wing, the initial method is modified. By processing velocity information acquired in a near-field plane, both the lift and induced drag was calculated for the trailing aircraft. Comparisons are made to directly measured loads and to results reported earlier. Directly measured lift and drag coefficients were found to agree with existing literature.

Gibbs, J. D., Vlachos, P. P. and Telionis, D. P.

"EXPERIMENTAL DETERMINATION OF LIFT AND LIFT DISTRIBUTIONS FOR WINGS IN FORMATION FLIGHT"

AIAA Paper No. 2005-843, Reno, NV, January 2005.

Methods to experimentally determine trailing vortex strengths and spanwise circulation distributions for two wings in formation flight using a flow measurement probe are presented. With these experiments we model compound aircraft flight either docked tip-to-tip, or flying in formation. Data were collected for the case of a full wing trailing a larger wing. The absence of fixed walls on either end of the wing permits the development of asymmetric shedding of vortices, and the determination of the asymmetric circulation distribution induced by the proximity of the leading wing. The pair consisted of a swept NACA 0012 non-cambered wing simulating one half of a leading aircraft and a rectangular cambered NACA 63-420 wing simulating the trailing aircraft. Velocity and vorticity distributions obtained along a near-field plane were processed to calculate wingtip vortex strengths. Vortex position instabilities and the shedding of vorticity inboard of the wingtips were observed. Circulation distributions for the trailing wing are measured. Comparisons are made to directly measured loads and to results reported earlier. Directly measured lift and drag coefficients were found to agree with existing literature.

Gibson, J. S.

"NON-ENGINE AERODYNAMIC NOISE INVESTIGATION OF A LARGE AIRCRAFT"

NASA CR-2378, October 1974, Lockheed-Georgia Company, Marietta, GA.

A series of flyover noise measurements have been accomplished utilizing a large jet transport aircraft with engine power reduced to flight idle. It was determined that the aerodynamic (non-engine) noise levels did occur in the general range that had been predicted by using small aircraft (up to 17,690 kg gross weight) prediction techniques. The test procedures used are presented along with discussions of

the effects of aerodynamic configuration on the radiated noise, identification of noise sources, and predicted aerodynamic noise as compared with measurements.

Gierens, K. M.

"NUMERICAL SIMULATIONS OF PERSISTENT CONTRAILS"

Vol. 30, March 1995, Institut für Physik der Atmosphäre, Wessling, Germany

Numerical (2D) simulations of persistent contrails have been performed. The simulations begin in the vortex phase (i.e. when the aircraft wake dynamics are dominated by the pair of downward travelling vortices) and pursue the evolution for half an hour. It will be shown that the lateral expansion of a contrail is mainly horizontal when the air inside it assumes a constant potential temperature during the vortex phase as a result of thermal isolation from the ambient air. If, however, the air inside the contrail becomes stably stratified as a result of strong thermal contact with a stably stratified environment, the lateral expansion will be more isotropic. The cross section spreading rate ranges from 110-240 meters squared per second. The expansion is mainly caused by the secondary and higher order vortices that develop in the reaction of the atmosphere on the downward travelling pair of primary vortices which in turn are produced by the aircraft itself. Humidity and temperature of the ambient air control the growth of the ice particles and, therefore, all properties that depend on crystal size and the overall ice production rate. Radiative cooling and release of latent heat are thermodynamically inefficient and do not induce convective motions in the contrail.

Gierens, K. M. and Strom, J.

"A NUMERICAL STUDY OF AIRCRAFT WAKE INDUCED ICE CLOUD FORMATION"

Journal of the Atmospheric Sciences, Vol. 55, No. 21, November 1, 1998, pp. 3253-3263

Numerical simulations of ice cloud formation in the wake of an aircraft flying at cruise altitude have been performed. The engine exhaust has been excluded from the simulations in order to study cloud formation due solely to aerodynamic effects. The ice is formed via homogeneous freezing nucleation of ambient haze droplets in the upwelling limbs of the vortex pair behind the aircraft. Properties of wake ice clouds are compared with properties of contrails obtained within situ measurements and recent simulations. In particular, the authors find that aerodynamically induced ice clouds are similar in microphysical and radiative respects to contrails that are formed from the nucleation of exhaust particles. This means that under cold and moist conditions contrails as young as 2-5 min may consist of similar amounts of aerodynamically produced and exhaust triggered ice crystals.

Gilbert, G. A.

"BUSINESS JET ACCIDENTS FOCUS ON WAKE VORTEX"

Business and Commercial Aviation, Vol. 74, Issue 2, February 1994, p. 18

Investigators believe wake vortices from Boeing 757s may have caused at least four accidents or incidents involving GA aircraft. These include the fatal crashes of two business jets: a Citation at Billings, Montana in December 1992 and a Westwind at Santa Ana, California in December 1993. In January, the FAA instructed ATC to provide specific Boeing 757 wake turbulence advisories, and agency administrator David Hinton sent a letter to all U.S. pilots reminding them of wake turbulence avoidance guidelines.

Gilbert, G. A.

"FAA'S WAKE-VORTEX HANDLING PROMPTS INTERNAL REVIEW"

Business and Commercial Aviation, Vol. 75, Issue 3, September 1994, p. 16

An internal FAA/DOT review critical of the way the FAA disseminated information about wake vortices generated by Boeing 757s calls for several improvements - especially in the agency's handling of safety issues. Prompting the review was the FAA's failure to act on reports of possible B-757 wake turbulence problems as early as 1988 and again in 1992. The agency did not issue any warnings or increase separation standards for smaller aircraft flying behind B-757s until two fatal accidents in 1993 involving corporate jets.

Gilbert, T.

"AERODYNAMIC INFLUENCES DURING MINIMUM INTERVAL TAKEOFFS AND AERIAL REFUELING"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 12-1 - 12-10

The concept and purpose of the Minimum Interval Takeoff (MITO) is to get a large number of aircraft off the ground safely in a relatively short period of time. The military routinely performs MITOs with as little as 12 seconds between aircraft. This spacing between aircraft can vary, depending upon weather conditions, aircraft configuration (performance factors) as well as type of aircraft. The very things that make MITOs potentially hazardous are the reasons behind the safe separation concept - wing tip vortices. The effects of a MITO are actually felt during the takeoff roll. Airspeed fluctuations as high as 20 knots can be experienced due to the preceding aircraft's wake. Slight wing rock can occur but is easily controllable. Due to the preceding aircraft's climb rate, downwash effects are minimal and not noticeable to the following aircraft once airborne. Wing tip vortices, however, are a large problem and if not properly compensated for, can be disastrous possibly leading to the loss of control of the aircraft.

Giles, M. B. and Cummings, R. M.

"WAKE INTEGRATION FOR THREE-DIMENSIONAL FLOWFIELD COMPUTATIONS: THEORETICAL DEVELOPMENT"

Journal of Aircraft, Vol. 36, No. 2, March-April 1999, pp. 357-373.

This paper examines the analytical, experimental, and computational aspects of the determination of the drag acting on an aircraft in flight, with or without powered engines, for subsonic/transonic flow. Using a momentum balance approach, the drag is represented by an integral over a crossflow plane at an arbitrary distance behind the aircraft. Asymptotic evaluation of the integral shows the drag can be decomposed into three components corresponding to streamwise vorticity and variations in entropy and stagnation enthalpy. These are related to the established engineering concepts of induced drag, wave drag, profile drag, and engine power and efficiency. This decomposition of the components of drag is useful in formulating techniques for accurately evaluating drag using computational fluid dynamics calculations or experimental data.

Gill, G. C.

"THE HELICOID ANEMOMETER, A LONG NEGLECTED BUT VALUABLE ANEMOMETER"

Atmosphere, Vol. 11, No. 4, 1973, pp. 145-155.

Although the helicoid anemometer has been known since 1887 (W. H. Dines) it was not until the 1940's that a rugged, accurate and reliable instrument was built (The Aerovane, by Bendix Friez). Some of the outstanding features of the helicoid anemometer are as follows: it is a primary sensor -- it is not essential to calibrate in a wind tunnel; its rate of turning is linearly proportional to wind speed over a wide speed range; some versions have a very low starting speed; and some helicoids, fixed in position, measure only that component of the wind that is parallel to the axis of the helicoid.

Gill, P. G.

"AVIATION TURBULENCE FORECAST VERIFICATION"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 13, 2016, Springer International Publishing Switzerland, pp. 261-284.

Forecast verification is an essential part of any forecast system. Verification results can be used in many ways: in the development process to ensure changes are leading to the desired improvements and to assure users and relevant authorities the forecasts have the required level of skill and can help to maximize the value a user gains from the forecast. In this section, we look at the challenges of verifying both deterministic and probabilistic turbulence forecasts. We investigate the different potential sources of truth data for use in verification with some discussion of the advantages and disadvantages of each. We also look at the possible methodologies and metrics that can be applied with some suggestions on the most appropriate ways to verify turbulence forecasts.

Gilliam, Jr., F. T.

"INVESTIGATION OF THE EFFECTS OF DISCRETE WING TIP JETS ON WAKE VORTEX ROLL UP"

Ph.D. Thesis, August 1983, Air Force Inst. of Tech., Wright-Patterson AFB, OH

A water tunnel experiment and a computational flow field model show that discrete wing tip jets can strongly affect the roll up of the wing tip vortex and apparently decrease its rolled up strength at moderate levels of blowing. The key factor in vortex alleviation was the extent of the local flow interactions between the discrete jets and the developing wing tip vortex. Vortex trajectory in both the spanwise and vertical directions was influenced by the jets. An outboard shift of the wing tip vortex indicated that discrete wing tip jets may be able to produce improved wing aerodynamics during cruise flight. The counterrotating pair of vortices generated by a jet in a cross flow were clearly seen in the water tunnel and appeared to be very effective in reducing the intensity of the wing vortex system. Two types of periodic secondary vortices were also observed in the water tunnel for heavy jet blowing. These were spin-off vortices which periodically developed in the rolling up tip vortex but rapidly spun outboard and above the wing; and entrained vortices which was a set of periodic vortices laterally connecting the wing tip vortex to the vortices embedded in the jet. These secondary vortices are oriented such that they will greatly accelerate the spreading of wake vorticity through the vortex stretching term of the Helmholtz equation. This influence was confirmed in the water tunnel tests.

Gillot, B. and Marais, C.

"PARTICIPATION OF METEO-FRANCE IN WAKE VORTICES STUDIES"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

To reduce aircraft separation standards defined by ICAO, Meteo-France has developed different wake vortices studies, as requested by the STNA (Service Technique de la Navigation Aérienne). In the first study, the effect of crosswind on wake vortices trajectory is analyzed by using the VORTEX model, developed by CERFACS (Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique). This model allows real-time evaluation of hazards associated with the wake vortices. The work has led to the definition of crosswind classes related to hazard duration, which corresponds to the time the two vortices stay inside the safety corridor (defined as the range <45 m from the runway axis). These classes depend on the number of runways and their distance. Regarding the configuration 'separation of 3NM on independent runway' two classes of crosswind are needed: smaller than 3 m/s and larger or equal to 3 m/s. The second study analyzes the evolution of wake vortices at small scale in 2D by using the French Meso-NH model, an atmospheric simulation code developed in cooperation between Meteo-France and the CNRS (Centre National de Recherche Scientifique). This model is initialized with the Idaho Falls experimental data. Different crosswind, stratification and wind profile are simulated for stable and mixed convective boundary layer. The work on the crosswind leads to about the same classes as with the VORTEX model. The VORTEX model could be improved in a further step by using the results on stratification and windshear.

Gilpin, T. J.

"A UK ASSESSMENT OF APPROPRIATE TECHNOLOGIES FOR DETECTING AND TRACKING WAKE VORTICES IN THE APPROACH AREA"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 51-1 - 51-20

In response to the signing of a Memorandum of Cooperation between the US FAA and the UK CAA on wake vortex research the UK was asked specifically to investigate technologies which might lead to a ground based real-time wake vortex detection and tracking unit. If the precise position and track of vortices in the approach area are accurately known then under some meteorological conditions it might be possible to safely decrease the separation and hence reduce delays in favorable conditions at runways. Initially three technologies were considered, laser, radar and sodar. A Memorandum of Cooperation was signed with the French DGAC who were supporting work on the detection of vortices by sodar leaving the UK to concentrate on laser and radar technology. This paper describes two recent field trials carried out in the UK using these technologies to attempt to detect wake vortices.

Gilruth, R. R. and Turner, W. N.

"LATERAL CONTROL REQUIRED FOR SATISFACTORY FLYING QUALITIES BASED ON FLIGHT TESTS OF NUMEROUS AIRPLANES"

NACA Technical Report No. 715, January 1941, Langley Memorial Aeronautical Laboratory, Hampton, VA.

An analysis has been made of the aileron control characteristics of numerous airplanes tested in flight by the National Advisory Committee for Aeronautics. In the correlation of satisfactory and unsatisfactory characteristics with measured values, it was found that the helix angle $pb/2V$, which expresses the lateral displacement of the wing tip in a given forward travel of the airplane, was the measure of the aileron effectiveness appreciated by the pilots. It was also found that regardless of size or category of the airplanes tested, which included pursuit, transport, training, and bomber types, a value of $pb/2V$ of 0.07 represented a criterion of minimum satisfactory aileron effectiveness. By the use of previously developed theory, the observed values of $pb/2V$ for the various wing-aileron arrangements were examined to determine the effective section characteristics of the various aileron types.

Gilson, W. H.

"RADAR MEASUREMENTS OF AIRCRAFT WAKES AT KWAJALEIN, R.M.I."

Airborne Windshear Detection and Warning Systems - Fifth and Final Combined Manufacturers' and Technologists' Conference, DOT/FAA/RD-94/14-II, Langley Research Center, Hampton, VA, July 1994, pp. 603-62.

A series of multi-frequency radar measurements of aircraft wakes at altitudes of 5,000 to 25,000 ft. were performed at Kwajalein, R.M.I., in May and June of 1990. Two aircraft were tested, a Learjet 35 and a Lockheed C-5A. The cross-section of the wake of the Learjet was too small for detection at Kwajalein. The wake of the C-5A, although also very small, was detected and measured at VHF, UHF, L-, S-, and C-bands, at distances behind the aircraft ranging from about one hundred meters to tens of

kilometers. The data suggest that the mechanism by which aircraft wakes have detectable radar signatures is, contrary to previous expectations, unrelated to engine exhaust but instead due to turbulent mixing by the wake vortices of pre-existing index of refraction gradients in the ambient atmosphere. These measurements were of necessity performed with extremely powerful and sensitive instrumentation radars, and the wake cross-section is too small for most practical applications.

Gimmestad, G. G., Papanicolopoulos, C. D., Richards, M. A., Sherman, D. L. and West, L. L.

"FEASIBILITY STUDY OF RADIOMETRY FOR AIRBORNE DETECTION OF AVIATION HAZARDS"

NASA/CR-2001-210855, June 2001, Georgia Tech Research Institute, Atlanta, GA.

Radiometric sensors for aviation hazards have the potential for widespread and inexpensive deployment on aircraft. This report contains discussions of three aviation hazards - icing, turbulence, and volcanic ash - as well as candidate radiometric detection techniques for each hazard. Dual-polarization microwave radiometry is the only viable radiometric technique for detection of icing conditions, but more research will be required to assess its usefulness to the aviation community. Passive infrared techniques are being developed for detection of turbulence and volcanic ash by researchers in this country and also in Australia. Further investigation of the infrared airborne radiometric hazard detection approaches will also be required in order to develop reliable detection/discrimination techniques. This report includes a description of a commercial hyperspectral imager for investigating the infrared detection techniques for turbulence and volcanic ash.

Ginevsky, A. S. and Zhelannikov, A. I.

"VORTEX WAKES OF AIRCRAFT"

Springer-Verlag Berlin Heidelberg, 2009 [English translation of book published by FIZMATLIT, Moscow, 2008].

This monograph covers the methods for mathematical modeling of vortex wakes behind aircraft at altitude and near the ground during takeoff and landing operations. The modeling is based on extensive use of the discrete vortex method and on the combination of this method with the integral method for computation of the turbulent boundary layer generated in the near-wall transverse flow induced by an aircraft's vortex system at takeoff and landing. In the latter case, the interaction between the aircraft's vortex wake and secondary vortices caused by boundary-flow separations is taken into consideration. The methods for simulation of the near and far vortex wakes of turbojet and propeller-driven aircraft are discussed separately. Examples of computed vortex wakes behind some Russian-built and Western aircraft are presented with due consideration for atmospheric turbulence, stratification and crosswinds at landing and takeoff. In modeling vortex wakes with the proposed methods the required computer execution time is three-four orders of magnitude less in comparison with known numerical methods. A nonlinear unsteady mathematical model is presented for predicting the motion of light aircraft encountering the vortex wake of a heavy aircraft and a possible severe upset of wake-penetrating aircraft. Computed data are compared with experimental results.

Gingras, D. R., Player, J. L. and Blake, W. B.

"STATIC AND DYNAMIC WIND TUNNEL TESTING OF AIR VEHICLES IN CLOSE PROXIMITY"

AIAA Paper No. 2001-4137, Montreal, Canada, August 2001.

Bihrlé Applied Research Inc. has developed unique capabilities for investigating the aerodynamic effects on aircraft in close formation. Wind-tunnel experiments were conducted at the Langley Full-Scale Tunnel using special hardware and computer equipment developed specifically for formation testing. It was demonstrated that static and dynamic force and moment data, as well as surface pressure data and wake survey data, can be acquired and utilized to analyze and model vehicle in close formation flight. The data acquired is well suited for use in flight vehicle simulation for development of control laws for automated formation flight and automated refueling. Unique to this wind tunnel testing was the simultaneous collection of force and moment data from two separate models positioned differently during each run. Also unique was the dynamic testing conducted to determine the control surface deflections required to trim the trail vehicle in various formation positions.

Giovannini, A. and Boisson, H.-C.

"DYNAMIC MIXED LES OF A VORTEX PAIR IN A TURBULENT CHANNEL"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

In order to determine the main features of an In-Ground-Effect vortex wake in a cross wind, Large-Eddy Simulations have been performed. The flow studied is a counter-rotating vortex pair evolving in a turbulent wall channel boundary layer. This study was developed to solve the test case retained for comparison for task 3.1.1-3 of the FAR-Wake project. The sub-grid scale model used is a Dynamic Mixed Model based on a double spatial filtering that takes account of energy backscatter in the interaction between resolved and unresolved turbulent fields. The numerical approach has been tested in a longitudinal vortex flow. First the transition to turbulence is simulated in the channel, and the vortex pair is introduced in the fully turbulent flow. Evolution of this vortex pair in the near wall region is analyzed. It is found that (1) for the upwind vortex when the wind velocity is low a rebound is active giving a weakening of the vortex hazard by 50 percent between non-dimensional time stations of 2 and 3, and (2) for the downwind vortex, the rebound is efficient for the axial flow equal to the decent velocity but it is inhibited for the axial flow equal to twice the descent velocity, due to a strong destruction process at shorter time. The weakening of the vortex hazard reaches 90 percent and the onset of this destruction process is earlier in time (between non-dimensional time of 1 and 3).

Giulietti, F., Innocenti, M., Napolitano, M. and Pollini, L.

"DYNAMIC AND CONTROL ISSUES OF FORMATION FLIGHT"

Aerospace Science and Tech., Vol. 9, Issue 1, January 2005, pp. 65-71

Two aspects of formation flight are addressed in this paper: dynamic modeling and formation control. In formation flight aircraft dynamics are coupled by aerodynamic effects due to the vortices leaving the lifting surfaces, such as changes in lift and drag forces and lateral/directional effects that do not appear in a steady-level 'isolated' flight. These aerodynamic effects are properly modeled with a three-dimensional code based on a Distributed Horse-Shoe Technique. A formation controller allowing both trajectory tracking and formation geometry keeping is then designed. It is shown that the designed controller yields satisfactory performance in a two-aircraft formation.

Giuni, M.

"FORMATION AND EARLY DEVELOPMENT OF WINGTIP VORTICES"

PhD Thesis, January 2013, University of Glasgow, Glasgow, Scotland.

Wingtip vortices are extremely important phenomena in fluid dynamics for their negative effects in many applications. Despite the many studies on this particular flow, the current understanding is still poor in providing a firm base for the design of effective tip geometry modifications and vortex control devices. A rectangular wing with squared and rounded wingtips was tested to identify the main mechanisms involved in the formation of the vortex on the wing and in its early development in the wake. The complementarity of several experimental techniques adopted, such as surface flow visualizations, wall pressure measurements, smoke visualizations, and stereoscopic particle image velocimetry (SPIV) gave a richer insight of the physics and the basic mechanisms of the vortex development. Furthermore, many configurations were tested exploring the effects of several parameters such as wing chord, aspect ratio, wingtip geometry, angle of attack and Reynolds number. The development of the vortex along the wing showed the formation of several secondary vortices which interacted with the primary vortex generating low frequency fluctuations. The structure of the flow at this stage was analyzed introducing a compact description through characteristic lines of the vortex system defined from the velocity vector field in the vicinity of the wing surface. The high spatial resolution achieved by the SPIV arrangement allowed a deeper understanding of the vortex structure in the early wake and the turbulence production and dissipation within the vortex core. The relaminarization process of the vortex core promoted by centrifugal motion was observed. The relation between vortex meandering, turbulence, secondary vortices, and wake sheet was discussed. A comparison of different methods for the averaging of instantaneous planar vector fields was performed showing the effects and importance of the meandering. An axial acceleration of the flow within the vortex was observed and the formation of different axial flow distributions was discussed. A minimum wake-like flow of 0.62 and a maximum jet-like flow of 1.7 times the freestream velocity were measured and a linear relation between a vortex circulation parameter and the axial velocity peak was found.

Giuni, M. and Benard, E.

"ANALYTICAL/EXPERIMENTAL COMPARISON OF THE AXIAL VELOCITY IN TRAILING VORTICES"

AIAA Paper No. 2011-0990, January 2011, Orlando, FL.

The axial velocity of a vortex is a parameter which is known to be strongly related to the vortex breakdown, yet to date a complete description of its physical origins has not been achieved. A series of experiments studying the vortex trailed from a NACA 0015 wing using stereoscopic particle image velocimetry is presented and the axial velocity studied in detail. The problem of centering the instantaneous vector fields is addressed showing a high sensitivity of the results from the centering method which is adopted. It is shown that a strong axial velocity excess exists and a linear relationship between the axial velocity and a circulation parameter of the vortex is shown. The experimental data are compared with the analytical descriptions of the velocity in the center of a simplified vortex giving new insights of the viscous effects in the development of the axial flow.

Giuni, M. and Green, R. B.

"VORTEX FORMATION ON SQUARED AND ROUNDED TIP"

Aerospace Science and Technology, Vol. 29, 2013, pp. 191-199.

The vortical flow originated from the tip of a NACA 0012 rectangular wing is described in its initial formation and development over a rounded and a squared tip. Smoke visualizations show the rolling-up kinematic and evolution of the vortical systems moving the plane towards the trailing edge. The presence of intense secondary vortices affects the primary vortex unsteadiness and shape during the formation and in the early wake. Stereoscopic Particle Image Velocimetry is used to describe vorticity, axial velocity, and turbulent kinetic energy distributions of the vortex during the formation and in the early wake at different angles of attack of the wing. The rolling-up of the vorticity sheet around the vortex system is strongly influenced by the vortex shape and the intensity of secondary vortices. Turbulence coming from secondary structures and shear layers is wrapped into the roll-up of the vortex and high levels of turbulence are measured in the vortex core. However, a laminar vortex core is observed for the lower angle of attack in the early wake. Comparing the meandering of the vortex for the two wingtip geometries, two different sources of the vortex fluctuation in the wake are identified: the interaction of secondary vortices moving around the primary vortex and the rolling-up of the vorticity sheet. Lastly, measurements in the wake of the wing at zero incidence are also presented showing a distinctive counter rotating vortex pair.

Giuni, M., Green, R. B. and Benard, E.

"INVESTIGATION OF A TRAILING VORTEX NEAR FIELD BY STEREOSCOPIC PARTICLE IMAGE VELOCIMETRY"

AIAA Paper No. 2011-0992, January 2011, Orlando, FL.

High spatial resolution experiments in the near field of a trailing vortex using a SPIV technique have been carried out. A particular attention on the measurement technique is presented highlighting the importance of the laser pulses delay between the two frames in a double-frame/single-pulse method and of the images processing characteristics in the evaluation of velocity profiles and turbulence quantities. The number of samples needed for the statistical convergence of the mean flow and the

turbulent quantities has also been found. A study on the vortex aperiodicity correction method has revealed how the instantaneous vector fields centering affects the velocity profiles across the vortex. The importance in the choice of the vortex quantity which is used for the vortex center detection is presented.

Gjessing, D. T., Hjelmstad, J. and Tønning, A.

"SYSTEM FOR DETECTION AND MEASUREMENT OF ATMOSPHERIC MOVEMENT"

US Patent 6,070,461, June 2000.

A system for the detection and measurement of atmospheric air movement irregularities such as wind velocity vector, wind shear, downdraft, clear air turbulence, aircraft induced vortices and turbulence, in particular along a glidepath near airports, whereby an air volume under investigation is illuminated by a radio wave transmitter with a beam of coherent electromagnetic energy and a resulting wave field is received and processed in processor means to derive information on the existence of said atmospheric irregularities and furthermore to give specific measurements of related parameters, comprising at least one receiver for said resulting wave field, which is due to scattering in said air volume, positioned at a bistatic location having a selected distance from said transmitter, characterized by acoustic transmitter means located between said transmitter and said at least one receiver, and adapted to emit acoustic waves into said air volume, with frequency and beamwidth of the acoustic waves chosen such that a resulting disturbance of the dielectric constant of air in said air volume, contributes to said scattering.

Gleyzes, C. and Pailhas, G.

"RESULTS OF THE STUDY OF THE MIRAGE G8'S WAKE AT THE F2"

DERAT-20/5025AYD, November 1987, Centre d'Etudes et de Recherches de Toulouse, Dept. d'Etudes et de Recherches en Aerothermodynamique, Toulouse, France

A detailed presentation is given of results from the second round of trials at the F2 (wind tunnel) of the Mirage G8's wake. Additional laser measurements were made, as well as soundings using a four hot-wire probe. Although the distance between probe stations was large, an attempt was made to determine the different elements of the model's wake. [In French.]

Glotov, G. F.

"INTERFERENCE BETWEEN A VORTEX FILAMENT AND SHOCK WAVES IN FREE FLOW AND IN NONISOBARIC JETS"

Uchenya Zepiski TsAGI, Vol. 20, No. 5, 1989, pp. 21-32.

The interaction between a vortex filament generated by a wing cantilever at angles of attack of 5-20 degrees and shock waves in free stream (Mach 1.8-3.5) in an under-expanded jet (Mach 1.0) was

investigated experimentally in the relative pressure range of 1.5-7. It is shown that the interaction between the vortex filament and a central shock wave in the jet leads to the formation of a freely suspended recirculation zone. Vortex breakdown limits are determined for a jet, a convergent nozzle, and supersonic flow at conical shock waves of maximum intensity.

Gloudemans, T., Van Lochem, S., Ras, E., Malissa, J., Ahmad, N. N. and Lewis, T. A.

"A COUPLED PROBABILISTIC WAKE VORTEX AND AIRCRAFT RESPONSE PREDICTION MODEL"

NASA-TM-2016-219193, May 2016, NASA Langley Research Center, Hampton, VA.

Wake vortex spacing standards along with weather and runway occupancy time, restrict terminal area throughput and impose major constraints on the overall capacity and efficiency of the National Airspace System. The National Aeronautics and Space Administration has been conducting research on characterizing wake vortex behavior in order to develop wake decay and transport prediction models. This paper presents a methodology for the development and integration of probabilistic wake vortex model with an aircraft response model for air traffic management applications. The two modules of the proposed system 1) probabilistic wake prediction, and 2) aircraft response to wake vortex encounter, are evaluated independently using data from field experiments and wind tunnel tests with favorable results. The methodology as described in this report is well-suited for systems-level design and safety analysis of new advanced air traffic management concepts as well as forensic reconstruction of accidents due to inadvertent wake encounters. It is also envisioned that at a later stage of maturity, these models could potentially be used operationally, in ground-based spacing and scheduling systems as well as on the flight deck.

Glushkov, N. N.

"ON DECREASING THE DIMENSION OF UNSTEADY AERODYNAMIC PROBLEMS FOR LOW SUBSONIC SPEEDS"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 151-163

The possibility has been investigated of a simplification of computing unsteady aerodynamic characteristics of an aircraft encountering the zone of disturbances behind a wake-generating aircraft. To model the unsteady aerodynamics of aircraft, the discrete vortex method was chosen. The problem of computing unit step functions for thin lifting surfaces in incompressible fluid was considered in a linear formulation. It was shown that the increments of aerodynamic forces due to vortex shedding into the flow are determined by velocity changes in the vicinity of the leading edge. This circumstance allows one to decrease the dimension of the problem and reduce it to the computation of the wing's aerodynamic loading in a steady flow, but with the section twists varying in time. Examples of the unit step functions' computations for wings are presented. Exact solutions were obtained for two-dimensional flow and a comparison was made between them and theoretical results. Corresponding

integral equations were obtained for the derivatives of unit step functions when passing from discrete vortex distributions to continuous ones. [In Russian.]

Glushkov, N. N.

"APPLICATION OF THE EQUIVALENT FORM METHOD TO THE PROBLEMS OF UNSTEADY AERODYNAMICS"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 185-191

The potentialities of simplifying the algorithms for computing unsteady aerodynamic characteristics are considered. The linear discrete vortex method is used. The flow is assumed incompressible. The case is considered of a stepped change in boundary conditions at a lifting surface, which necessitates calculating transient functions. The time changing of aerodynamic loads on the wing is connected with corresponding changes in the form of an equivalent wing immersed in a uniform flow. The wing aerodynamic loads are shown to be only dependent on the time changing of the sectional twist angles of the equivalent wing. The forms of the wing chordwise sections are not changed. Because of this the problem dimensionally is reduced by one geometric variable. This substantially simplifies the computation of unsteady loads at low flight speeds (in takeoff and landing).

Glushkov, N. N., Dyachevsky, A. P. and Mikhailov, Y. S.

"APPROXIMATE METHOD FOR TAKING INTO CONSIDERATION THE NONLINEAR EFFECTS WHEN COMPUTING AIRCRAFT AERODYNAMIC CHARACTERISTICS IN A NONUNIFORM VELOCITY FIELD"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 180-184.

An engineering method is proposed for assessing nonlinear components of aerodynamic forces and moments exerted on an aircraft encountering the vortex flow generated by a leading aircraft. The method is based on the use of a linear theory with constraints placed on circulation strengths around wing sections. The constraints result in the nonlinear variations of aerodynamic characteristics. Computed results are compared with experimental data for the aircraft model immersed in the nonuniform flow field.

Goedecke, G. H., Ostashev, V. E., Wilson, D. K. and Auvermann, H. J.

"QUASI-WAVELET MODEL OF VON KARMAN SPECTRUM OF TURBULENT VELOCITY FLUCTUATIONS"

Boundary-Layer Meteorology, Vol. 112, 2004, pp. 33-56.

The von Karman spectra of turbulent temperature and velocity fluctuations have been widely used in the literature on turbulence and electromagnetic, seismic, and acoustic wave propagation in random media. In this paper we provide a phenomenological motivation for the von Karman velocity spectrum in terms of the quasi-wavelet model of turbulence developed recently. In this model, turbulence is represented as a superposition of self-similar localized eddies of many different scales. We find a functional form for these eddies that yields the von Karman velocity spectrum exactly. We also show that other eddy functions produce velocity spectra that have the same general form as the von Karman spectrum, and we consider possible quasi-wavelet representations of the 'Kansas' and the '-1' spectrum. We also present a systematic determination, based on turbulence similarity theories, of the parameters of the von Karman spectra of temperature and velocity fluctuations in an unstable atmospheric boundary layer.

Goerttler, A., Brankmann, J. N., Schwermer, T., Gardner, A. D. and Raffel, M.

"TIP-VORTEX INVESTIGATION ON A ROTATING AND PITCHING ROTOR BLADE"

Journal of Aircraft, Vol. 55, No. 5, September-October 2018, pp. 1792-1804.

The blade-tip vortex of a rotating and pitching DSA-9A blade was investigated numerically and experimentally. Numerical computations were performed using DLR, German Aerospace Center's finite volume solver TAU, and experimental data were gathered by using particle image velocimetry carried out in a stereoscopic setup at the rotor test facility in Gottingen. Algorithms deriving the vortex position, swirl velocity, circulation, and core radius were implemented. The agreement is better the lower the wake age is, with numerical dissipation enlarging the blade-tip vortex in an artificial manner with increasing wake age. Nevertheless, the numerical simulations can predict swirl velocity and circulation well and help understanding the growth and development of the blade-tip vortices. A comparison with a nonrotating version of this blade showed that the circulation of the nonrotating blade was in the same order.

Goff, R. W.

"AIRCRAFT WAKE VORTEX BEHAVIOR STUDY, VORTICES AND RUNWAY UTILIZATION"

ER73-4300, July 1973, Raytheon Company, Sudbury, M.

This report contains a survey and description of Air Traffic Control equipment which may be modified to provide the warning signal for a vortex detection system (the vortex warning device will alert landing aircraft of a vortex hazard). Since an important aspect of implementing new Air Traffic Control equipment is its integration with existing equipment and procedures, general information relevant to that problem is also provided.

Goff, R. W.

"STUDY OF THE PERFORMANCE REQUIREMENTS OF A VORTEX MONITORING SYSTEM"

DOT-TSC-141-1, March 1972, Raytheon Company, Sudbury, MA

This study involved four basic task items. The first was a general review of the characteristics of trailing vortex wakes. The second task item involved the generation of envelopes showing the expected vortex drift for the Boeing 747 and 727 aircraft. The third task item was an investigation of the environmental factors with which a vortex monitoring system would interact. The final task item was the application of the vortex drift data and operational usage considerations to the investigation of the performance requirements for a vortex monitoring system.

Goff, R. W.

"AIRCRAFT WAKE VORTEX BEHAVIOR STUDY"

ER73-4319, August 1973, Raytheon Company, Sudbury, MA

This report presents an analysis of the variations in wind magnitude and direction occurring at various times of day at Logan and Kennedy Airports, and an analysis of the aircraft spacing required to preclude an aircraft-vortex encounter in the approach corridor beyond the middle marker.

Gold, N. and Visser, K. D.

"AERODYNAMIC EFFECTS OF LOCAL DIHEDRAL ON A RAKED WINGTIP"

AIAA Paper No. 2002-0831, Reno, NV, January 2002

An experimental study was conducted to examine the impact of dihedral in the tip region of a wing on the induced drag as previous theoretical work has indicated a potential for drag reduction. Wake profiles were obtained with a seven-hole probe for a systematic variation of the dihedral and sweep of a raked tip on a 30 swept wing. These profiles were analyzed with the Boeing Universal Wake Survey Data Analysis Code to obtain lift and drag distributions. The data indicated that the tips with negative dihedral, and associated smaller span, yielded a lower induced drag than the greater span, zero dihedral configuration. The tips with positive dihedral showed no decrease of induced drag, within experimental error, compared to the zero-dihedral case. The raked tip with the lower sweep angle exhibited a lower induced drag than the tip with the higher sweep in all cases. Several unexpected dynamics were observed in the flow field, possibly because of the highly curved tip. A second vortical structure was present inboard of the main trailing vortex and the axial velocity in the trailing vortex displayed a dual 'jet like' (high velocity) and 'wake like' (low velocity) nature. Lift and drag distributions indicated that this second vortex locally decreased the lift and increased the induced drag.

Goldshtik, M. and Hussain, F.

"THE NATURE OF INVISCID VORTEX BREAKDOWN"

Phys. Fluids, Vol. 9, No. 2, February 1997, pp. 263-265

We show that vortex breakdown appears as a jump bifurcation due to structural instability of swirling flows when their solution locally fails to exist and the flow transits to another stable or metastable state. The flow pattern inside the steady separation zone and, consequently, the vortex breakdown features depend on the flow history. Therefore, we consider the flow pattern inside the separation zone. The stagnation zone model (without velocity jump) excels the traditional analytic continuation method (leading to a recirculation zone) in that solutions always exist, and, for large enough inflow swirl, exhibit non-uniqueness and folds due to smooth variations of flow parameters, thus predicting the experimentally observed hysteretic jump transitions.

Goldstein, A. and Meyer, J. W.

"ISOLATED AND CASCADE AIRFOILS WITH PRESCRIBED VELOCITY DISTRIBUTION"

NACA TR-869, 1947, Langley Aeronautical Laboratory, Langley Field, VA

An exact solution of the problem of designing an airfoil with a prescribed velocity distribution on the suction surface in each uniform flow of an incompressible perfect fluid is obtained by replacing the boundary of the airfoil by vortices. By this device, a method of solution is developed that is applicable both to isolated airfoils and to airfoils in cascade. The conformal transformation of the designed airfoil into a circle can then be obtained and the velocity distribution at any angle of attack computed. Numerical illustrations of the method are given for the airfoil in cascade.

Goldstone, L.

"AN INVESTIGATION INTO WAKE TURBULENCE INCIDENTS"

CAA Report DTRD/7301, November 1973, Civil Aviation Authority, London, England.

A working group was set up in March 1972 by the Director of Technical Research and Development to consider wake turbulence incidents reported in the United Kingdom from January 1972. The paper contains an analysis of these incidents and presents certain conclusions regarding factors which are relevant to the formation and persistence of the wake.

Golubev, V., Kazarin, P., Moreno, C. and MacKunis, W.

"ON WAKE VORTEX SAFETY ANALYSIS AND CONTROL FOR UAV"

31st Congress of the International Council of the Aeronautical Sciences (ICAS 2018), Paper 11.7.4, September 2018, Belo Horizonte, Brazil.

External disturbances, such as turbulence wind gust and upstream wake vortex can significantly affect the dynamics and flight trajectory of an unmanned aerial vehicle (UAV). These effects can pose danger to UAV. Thus, the integration of Unmanned Aerial Systems (UAS) into National Airspace System (NAS) requires close consideration of these effects. This paper presents a robust nonlinear control method that can be proven to achieve altitude and roll regulation in the presence of several types of

disturbances such as wake vortex and wind gust disturbance. Side-by-side simulation comparisons with H sub infinity linear control method are provided. The results demonstrate the capability of the proposed nonlinear controller to asymptotically reject disturbances in the presence of parametric uncertainty. In addition, the nonlinear controller is designed with a computationally simplistic structure, which does not require complex calculations or function approximations in the control loop. Hence, the proposed controller is a great choice for small UAV applications with limited computational resources.

Gomez, S., Gilkey, L. N., Kaiser, B. E. and Poroseva, S. V.

"COMPUTATIONAL ANALYSIS OF A TIP VORTEX STRUCTURE SHED FROM A BIO-INSPIRED BLADE"

AIAA Paper 2014-3253, June 2014, Atlanta, GA.

This study analyzes the effects that a bio-inspired blade shape has on the size and structure of a tip vortex. The blade prototype was selected based on the analysis of various insect orders with the purpose of finding wing profiles most suitable for the design of small rotorcraft propellers. Flow simulations are conducted around the bio-inspired blade and in its near wake using commercial CFD software Star-CCM+. Results are compared with those for a rectangular blade. A vortical structure is captured downstream of both blades. Flow data related to these structures is used to show that the bio-inspired shape produces weaker vortices, making it more desirable for rotorcraft implementation.

Gonzalez, L M. and Theofilis, V.

"TEMPORAL STABILITY ANALYSIS OF TWO-VORTEX SYSTEMS"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

Highly resolved solutions of the two-dimensional incompressible Navier-Stokes and continuity equations, describing the evolution of a counter-rotating pair of vortices, have been obtained accurately and efficiently by spectral collocation methods and an eigenvalue decomposition algorithm. Such solutions have formed the basic state for subsequent three-dimensional BiGlobal eigenvalue problem (EVP) linear instability analyses, which monitor the modal response of these vortical systems to small-amplitude perturbations, periodic along the homogeneous axial spatial direction, without the need to invoke an assumption of azimuthal spatial homogeneity. A finite-element methodology (FEM) has been adapted to study instability of vortical flows and has been validated on the Batchelor vortex. Subsequently, the instability of the counter-rotating dipole has been analyzed; aspects monitored have been the dependence of the results on (i) the Reynolds number, (ii) the value of the (non-zero) axial velocity considered and (iii) the time at which the quasi-steady basic flow has been monitored. Essential to the success of the analysis has been the appropriate design of a calculation mesh, as well as exploitation of the symmetries of the basic state. The spatial structure of the amplitude functions of all unstable eigenmodes reflects the inhomogeneity of the basic state in the azimuthal spatial direction, thus providing a-posteriori justification for the use of the BiGlobal EVP concept.

Goodhart, H. C. N.

"A NOTE ON THE MEASUREMENT OF THE INDUCED DRAG FACTOR (k) OF A GLIDER"

Technical Soaring, Vol. I, No. 4, 1972, pp. 7-9.

There appears to be a good case for treating lift dependent drag as being composed of two separate terms varying as $(C_{sub l})^2$. One is purely the induced drag (with a k value to cover non-ellipticity of lift distribution) which is inversely proportional to aspect ratio. The other is the variation of wing profile drag coefficient and is independent of aspect ratio. In the Reynolds Number range normally used by gliders and for Wortmann wing sections, it appears that this variation of wing profile drag coefficient contributes a slope of about 0.0038 to the $((C_{sub d})/((C_{sub l})^2))$ plot.

Goodman, T. R.

"THE VORTEX CORE JET NEAR THE POINT OF GENERATION"

72-91, April 1972, Oceanics Inc., Plainview, NY

Near the point of generation of a wing tip vortex the axial velocity in the vortex core can be considerably greater than the free stream velocity. The present analysis describes the velocity field under these circumstances and shows that a self-similar solution exists that satisfies all the boundary conditions. The resulting two-point boundary value problem is solved on a digital computer and shows qualitative agreement with experiments.

Goparaju, K. and Zhuang, M.

"NUMERICAL SIMULATION OF WINGTIP VORTICES"

AIAA Paper No. 2012-3328, June 2012, New Orleans, LA.

A numerical study of the formation and propagation of the tip vortices from a round-tip wing is performed. The application of a standard eddy viscosity model resulted in an extremely diffused vortex downstream of the wing which does not corroborate with the experimental results. Applying a modification to this model by changing the way in which eddy viscosity is produced dramatically improves the prediction of the vortical structures. The results indicate that a decent level of accuracy can be achieved by using lower order numerical schemes albeit only in the near wake of the wing.

Gordan, B. W., Pakmehr, M. and Rabbath, C. A.

"STATE-SPACE MODELING AND IDENTIFICATION OF DELTA WING VORTEX-COUPLED ROLL DYNAMICS"

J. Aircraft, Vol. 46, Jan.-Feb. 2009, pp. 36-45

This paper develops a new state-space model for vortex-coupled 65-degree delta wing aircraft system based on a modified nonlinear indicial response method combined with an internal state-space representation. Relationships between vortex breakdown location, rolling moment coefficient, and roll angle dynamics are determined. The state-space equations derived are subject to state delays and are also nonlinear in the vortex-coupled rolling moment coefficient. Linear and nonlinear parameter identification methods are developed to empirically estimate the rolling moment coefficient as a function of the roll angle and primary vortex breakdown locations. A comparison between numerical simulations and experimental data indicates close agreement for several different initial conditions.

Gordon, A. A.

"METHOD AND APPARATUS FOR MICROBURST AND WAKE TURBULENCE DETECTION FOR AIRPORTS"

U.S. Patent 5,262,773, Nov. 1993

A method and apparatus was developed for detecting specialized meteorological conditions such as a microburst and the wind condition generated behind an aircraft known as wake turbulence. The method and apparatus of the present invention is designed to display the location of the microburst directly on the flight controller's monitoring screen with the flight controller then being able to so inform any pilot of an aircraft of the microburst so that the pilot can take evasive action. The display on the flight controller's screen is to be in color. The displaying of the microburst on the screen is to be by means of a computer which utilizes as inputs the conventional aircraft surveillance radar, weather radar and ground radar as well as additional inputs of wind direction and velocity information obtained from detection devices mounted directly adjacent to the aircraft runway and along the approach and take-off areas for the runway.

Gordon, A. A.

"SYSTEM FOR DETECTING AND VIEWING AIRCRAFT-HAZARDOUS INCIDENTS THAT MAY BE ENCOUNTERED BY AIRCRAFT LANDING OR TAKING-OFF"

US Patent 5,657,009, August 1997

A system and method has been developed for detecting and viewing aircraft hazardous incidents such as flying aircraft and meteorological phenomena which includes microbursts, thunderstorms, tornadoes, and the wake turbulence of aircraft. The aircraft hazardous incidents are positionally and horizontally displayed to the pilot on a display, that is located in the aircraft cockpit, in relation to the flight path of the aircraft. The timely displaying of any of the aircraft hazardous incidents permits the pilot to take evasive action to avoid a potentially dangerous incident.

Gorstein, M.

"WAKE VORTEX DETECTION AND AVOIDANCE SYSTEMS"

USSR/US Aeronautical Technology Symposium, Moscow, USSR, July 1973.

A Wake Vortex Avoidance System (WVAS) to improve air transport safety and airport efficiency is being developed by the Transportation Systems Center for the FAA. The WVAS will detect and/or predict the current movement of vortices in nearby airport corridors, assess them as potential hazards to following aircraft, and provide warning to controllers and pilots to prevent hazardous encounters. The paper briefly discusses vortex behavior characteristics, vortex sensors, an in-process experimental program, and several possible wake vortex avoidance system concepts.

Gorstein, M., Hallock, J. N. and McWilliams, I. G.

"AIRCRAFT WAKE VORTEX AVOIDANCE SYSTEMS"

Proceedings of Electronics and Aerospace Systems Convention, IEEE, 1972, pp. 64-69

The behavior, detection, and prediction of the motion of aircraft wake vortices in the airport environment is discussed. Preliminary designs of wake vortex avoidance systems based upon the current assessment of aircraft vortex hazards are presented.

Gorstein, M., Hallock, J. N., McWilliams, I. G. and Goff, R. W.

"SYSTEM PERFORMANCE REQUIREMENTS FOR MONITORING TRAILING VORTICES IN A TERMINAL ENVIRONMENT"

National Aerospace Electronics Conf., Dayton, OH, May 1971

The paper discusses the performance requirements for systems capable of monitoring trailing vortices in three situations: (1) the approach and departure corridors, (2) between adjacent runways, and (3) at runway intersections. The monitoring requirements are shown to depend upon the vortex characteristics, the airport-runway geometry, and the operations characteristics of the airport (separation standards, runway usage and runway selection based upon the wind velocity). The significance of these factors are discussed and examples are given for several vortex monitoring situations at Logan Airport in Boston.

Gorton, S. A., Berry, J. D., Hodges, W. T. and Reis, D. G.

"FLOW ENVIRONMENT STUDY NEAR THE EMPENNAGE OF A 15-PERCENT SCALE HELICOPTER MODEL"

NASA-TP-2000-210085, March 2000, NASA Langley Research Center, Hampton, VA

Development of advanced rotorcraft configurations has highlighted a need for high-quality experimental data to support the development of flexible and accurate analytical design tools. To provide this type of data, a test program was conducted in the Langley 14- by 22-Foot Subsonic Tunnel to measure the flow near the empennage of a 15-percent scale powered helicopter model with an operating tail fan. Three-component velocity profiles were measured with laser velocimetry (LV) one

chord forward of the horizontal tail for four advance ratios to evaluate the effect of the rotor wake impingement on the horizontal tail angle of attack. These velocity data indicate the horizontal tail can experience unsteady angle of attack variations of over 30 degrees due to the rotor wake influence. The horizontal tail is most affected by the rotor wake above advance ratios of 0.10. Velocity measurements of the flow on the inlet side of the tail fan were made for a low-speed flight condition using conventional LV techniques. The velocity data show an accelerated flow near the tail fan duct, and vorticity calculations track the passage of main rotor wake vortices through the measurement plane.

Gorton, S. A., Berry, J. D., Hodges, W. T. and Reis, D. G.

"ROTOR WAKE STUDY NEAR THE HORIZONTAL TAIL OF A T-TAIL CONFIGURATION"

Journal of Aircraft, Vol. 39, No. 4, July-August 2002, pp. 645-653

Development of advanced rotorcraft configurations has highlighted a need for high-quality experimental data to support the development of robust and accurate analytical design tools. To provide high-quality experimental data, a test program was conducted in the NASA Langley Research Center 14- by 22-Foot Subsonic Tunnel to measure the flow near the empennage of a 15% scale powered helicopter model with an operating tail fan and a T-tail configuration. Three-component velocity profiles were measured forward of the helicopter tail for four advance ratios using laser velocimetry to evaluate the effect of the rotor wake impingement on the horizontal tail angle of attack. These velocity data indicate the horizontal tail can experience unsteady angle-of-attack variations of over 30 deg due to the rotor wake influence. The horizontal tail is most affected by the rotor wake at and above advance ratios of 0.10.

Gossler, A. A. and Marshall, J. S.

"SIMULATION OF NORMAL VORTEX-CYLINDER INTERACTION IN A VISCOUS FLUID"

J. Fluid Mech., Vol. 431, 2001, pp. 371-405.

A computational study of three-dimensional vortex-cylinder interaction is reported for the case where the nominal orientation of the cylinder axis is normal to the vortex axis. The computations are performed using a new tetrahedral vorticity element method for incompressible viscous fluids, in which vorticity is interpolated using a tetrahedral mesh that is refit to the Lagrangian computational points at each timestep. Fast computation of the Biot-Savart integral for velocity is performed using a box-point multipole acceleration method for distant tetrahedra and Gaussian quadrature for nearby tetrahedra. A moving least-square method is used for differentiation, and a flux-based vorticity boundary condition algorithm is employed for satisfaction of the no-slip condition. The velocity induced by the primary vortex is obtained using a filament model and the Navier-Stokes computations focus on development of boundary-layer separation from the cylinder and the form and dynamics of the ejected secondary vorticity structure. As the secondary vorticity is drawn outward by the vortex-induced flow and wraps around the vortex, it has a substantial effect both on the essentially inviscid flow field external to the boundary layer and on the cylinder surface pressure field.

Gottschall, J.

"GALION LIDAR PERFORMANCE VERIFICATION"

Technical Report, May 2013, Fraunhofer Institute for Wind Energy and Energy System Technology, Bremerhaven, Germany.

The observed performance of the Galion Lidar in the considered test setup, expressed in the presented verification results, meets the ScurrEnergy in-house criteria (i.e. the OLS regression slope is within 2 percent of unity, and R-squared greater than 0.98), indicating an acceptable performance of the device under test. Given that the measurements were performed in moderately complex (and definitely not perfectly flat) terrain, and that the Galion Lidar was operated in a mode that is not aimed at a best possible agreement with the reference measurements but has further advantages, the results of the verification test indicate a good agreement with the reference mast. The arc scan mode of operation may be recommended for applications where a horizontal distance between the location of the measurement device and its measurements is necessary, e.g. for a power performance assessment offshore with the Galion Laser installed on the transition piece of the test turbine. It is expected that the measurement uncertainties for such an application are even smaller than for the presented Galion Laser performance verification since the influences of the terrain would be less significant for an offshore site.

Gottschall, J., Courtney, M. S., Wagner, R., Jorgensen, H. E. and Antoniou, I.

"LIDAR PROFILERS IN THE CONTEXT OF WIND ENERGY -- A VERIFICATION PROCEDURE FOR TRACEABLE MEASUREMENTS"

Wind Energy, Vol. 15, 2012, pp. 147-159.

The need for measuring wind speed and direction at greater heights and at several levels simultaneously gains importance as wind turbines become larger and higher. For this purpose, remote-sensing profilers become very attractive for resource assessment and power performance testing. However, the existing standards only permit the use of cup anemometers as standard instruments. The main issue preventing the use of remote sensors in such standards is the need to maintain the traceability of the measurements in the international standard system. In this paper, we describe a verification procedure for lidar profilers that enables us to achieve the required traceability. The procedure is based on a direct comparison of the measurements from the lidar and reference sensors mounted on a mast at various height levels. First, the data are corrected and filtered to obtain a representative data set ensuring a repeatable test. Second, a linear regression is applied to the data for each height. The third step is a bin-average analysis of the lidar error, i.e. the difference between the lidar and reference measurements, forming the basis for the ensuing uncertainty estimation. The results of the verification test are both used to correct the lidar measurements and to derive a corresponding uncertainty budget. A significant limitation of the procedure is the considerable uncertainty introduced by the reference sensors themselves. The decision as to whether to apply the

derived correction as a lidar calibration or not therefore mainly depends on the interpretation of this reference uncertainty and the assumed and observed biases.

Govindarajan, B. M. and Leishman, J. G.

"CURVATURE CORRECTIONS TO IMPROVE THE ACCURACY OF FREE-VORTEX METHODS"

Journal of Aircraft, Vol. 53, No. 2, March-April 2016, pp. 378-386.

The accuracy of discretized induced velocity calculations using straight-line vortex segmentation has been examined using an induced velocity correction (curvature correction) based on a curved element with a thin core. The validity of the curvature correction has been evaluated for the prediction of helicopter rotor wakes using a free-vortex method. Numerical techniques were developed to incorporate the correction into the self-induced velocity calculations to improve the accuracy for a given discretization or to reduce the discretization for a required accuracy or computational cost. The correction was analyzed in detail to understand its validity based on its thin-core assumptions and to quantify the effect of the correction as it affects the evolution of the rotor wake. It is shown that, while the inclusion of the curvature correction can, in some cases, improve the accuracy of the induced velocity calculation for a given level of discretization, its applicability to helicopter wake problems is not guaranteed or universal.

Govindarajan, B., Leishman, J. G. and Gumerov, N. A.

"PARTICLE-CLUSTERING ALGORITHMS FOR THE PREDICTION OF BROWNOUT DUST CLOUDS"

AIAA Journal, Vol. 51, No. 5, May 2013, pp. 1080-1094.

Particle-clustering methods have been explored for application to the problem of predicting brownout conditions, which can occur when a rotorcraft operates over surfaces covered with loose sediment and stirs up large dust clouds that impede the pilot's outward visibility. A significant issue in such simulations is the tracking of the very large number of particles needed to predict with acceptable fidelity the dual-phase flow properties and optical characteristics of the dust clouds. To this end, computationally efficient Lagrangian approaches were explored for the simulation of dilute carrier-particle suspensions at low Reynolds numbers of the relative particle motion. The algorithms examined were the Gaussian method, the k-means method, and Osipov's method, which were all compared in terms of their accuracy versus computational cost against solutions obtained by directly solving for the individual particle motions. Specific results were computed for a prototypical flow field that mimics the highly unsteady, two-phase vortical particle flow responsible for the development of brownout conditions. It is shown that although clustering algorithms can be problem dependent and have bounds of applicability, in some conditions they offer the potential to significantly reduce the computational costs of brownout dust cloud simulations while still retaining good accuracy.

Govindaraju, S. P. and Saffman, P. G.

"FLOW IN A TURBULENT TRAILING VORTEX"

Phys. Fluids, Vol. 14, No. 10, October 1971, pp. 2074-2080

The structure of turbulent line vortices is examined. A general argument is constructed to show that the vortex must develop an overshoot of circulation if it entrains fluid at a rate greater than that due to molecular diffusion. A weak hypothesis on the distribution of Reynolds stress leads to the logarithmic profile of Hoffman and Joubert and an estimate of the maximum Reynolds stress. The results of a turbulence model due to Saffman are presented and shown to be poor.

Goyal, A., Saraf, A., Patel, A. and Pashilkar, A.

"ANALYSIS OF EFFECT OF WAKE VORTICES ON AIR DATA SENSORS"

Symposium on Applied Aerodynamics and Design of Aerospace Vehicle, November 2011, Bangalore, India.

An essential part of operational clearance of a new aircraft is to certify that it is safe to fly even when wake vortices generated by another aircraft are encountered. For certification, it must be demonstrated that the aircraft can safely cross the wake at a certain separation distance. When the wake is encountered, air data sensors that measure the directional of airflow in terms of Angle of Attack (AOA/Alpha), Angle of Side Slip (AOSS/Beta/SSA) and pressures (Total and Static Pressure) show large fluctuations. The ADS measurements are used for feedback to the fly-by-wire control laws. These large and rapid fluctuations in the ADS signals affects the commands generated by the fly-by-wire control laws and in turn results in generating high loads on the aircraft. Therefore, before actual flight tests it is necessary to predict the behavior of Air Data System (ADS) encountering the wake. Appropriate wake encounter protection features should be incorporated in the ADS algorithms. The behavior of the ADS including the wake protection features during wake must be cleared in a simulation environment. The simulation environment for wake analysis, behavior of the ADS measurements with and without wake protection features are presented in this paper for a generic high-performance aircraft. Paper also presents the wake protection features incorporated in the ADS algorithms.

Grabowski, W. J. and Berger, S. A.

"SOLUTIONS OF THE NAVIER-STOKES EQUATIONS FOR VORTEX BREAKDOWN"

J. Fluid Mech., Vol. 75, Part 3, June 1976, pp. 525-544

A numerical investigation of vortex breakdown has been undertaken in an attempt to understand its properties, and the mechanisms responsible for it. Solutions of the full steady axisymmetric Navier-Stokes equations for breakdown in an unconfined viscous vortex have been obtained for core Reynolds numbers up to 200, for a two-parameter family of assumed upstream velocity distributions. Diffusion and convection of vorticity away from the vortex core, and the strong coupling between the circumferential and axial velocity fields in highly-swirling flows, are shown to lead to stagnation and

reversal of the axial flow near the axis. The various theories of vortex breakdown are considered in light of the present numerical solutions.

Gracey, W.

"MEASURED MOMENTS OF INERTIA OF 32 AIRPLANES"

NACA TN-780, October 1940, Langley Aeronautical Lab., Langley Field, VA.

A compilation of the experimentally determined moments of inertia of 32 airplanes is presented. The measurements were obtained at the laboratories of the NACA by means of a pendulum method. The airplanes tested are representative of several types of aircraft of gross weight less than 10,000 pounds. The results are presented in coefficient as well as in dimensional form. An elementary analysis of the data disclosed the possibility of grouping the results according to wing type of the airplane, as low-wing monoplanes, parasol and high-wing monoplanes, and biplanes. The data are shown to provide a convenient means of rapidly estimating the moments of inertia of other airplanes. A three-view drawing of each of the 32 airplanes is included.

Gracey, W.

"THE EXPERIMENTAL DETERMINATION OF THE MOMENTS OF INERTIA OF AIRPLANES BY A SIMPLIFIED COMPOUND-PENDULUM METHOD"

NACA TN-1629, June 1948, Langley Aeronautical Lab., Langley Field, VA.

A simplified compound-pendulum method for the experimental determination of the moments of inertia of airplanes about the x and y axes is described. The method is developed as a modification of the standard pendulum method reported previously in NACA report, NACA-467. A brief review of the older method is included to form a basis for discussion of the simplified method.

Graftieaux, L., Michard, M. and Grosjean, N.

"COMBINING PIV, POD AND VORTEX IDENTIFICATION ALGORITHMS FOR THE STUDY OF UNSTEADY TURBULENT SWIRLING FLOWS"

Measurement Science and Technology, Vol. 12, 2001, pp. 1422-1429.

Particle image velocimetry (PIV) measurements are made in a highly turbulent swirling flow. In this flow, we observe a coexistence of turbulent fluctuations and an unsteady swirling motion. The proper orthogonal decomposition (POD) is used to separate these two contributions to the total energy. POD is combined with two new vortex identification functions, γ_1 and γ_2 . These functions identify the locations of the center and boundary of the vortex based on the velocity field. The POD computed for the measured velocity fields shows that two spatial modes are responsible for most of the fluctuations observed in the vicinity of the location of the mean vortex center. These two modes are also responsible for the large-scale coherence of the fluctuations. The POD computed from

the gamma sub 2 scalar field shows that the displacement and deformation of the large-scale vortex are correlated to these modes. We suggest the use of such a method to separate pseudo-fluctuations due to the unsteady nature of the large-scale vortices from the fluctuations due to small-scale turbulence.

Graham, A. and Raper, D. W.

"TRANSPORT TO GROUND OF EMISSIONS IN AIRCRAFT WAKES. PART I: PROCESSES"

Atmospheric Environment, Vol. 40, Issue 29, September 2006, pp. 5574-5585

An aircraft exerts a downward force on the air, so aircraft exhausts tend to descend toward the ground within the aircraft's wake. The wake of an airplane descends in an essentially inviscid and thus long-lived manner, through the action of a pair of trailing counterrotating vortices on one another. The vortices derive from the circulation about the wings yielding the lift. Exhaust pollutants may thus be conveyed to the ground close to airports, far more effectively than through ambient atmospheric dispersion alone, as has hitherto been assumed occurs within air-quality models. The presence of the vortices in the vicinity of airports is well-established, as it is the need to wait for their decay or movement out of the flight corridor -- for the safety of the following aircraft -- that caps departure and arrival rates at busy periods. The dynamics of the transport are elucidated, so that the impact of the transport on pollutant concentrations at ground level in an airport environment may be established.

Graham, A. and Raper, D. W.

"TRANSPORT TO GROUND OF EMISSIONS IN AIRCRAFT WAKES. PART II: EFFECT ON NO_x CONCENTRATION IN AIRPORT APPROACHES"

Atmospheric Environment, Vol. 40, Issue 30, September 2006, pp. 5824-5836

Predictions as to the transport of aircraft NO_x emissions to ground level in the vicinity of an airport are made, taking account of the vortical dynamics of the aircraft wake. A model is used to calculate mean ground-level concentrations. It employs a kinematic approach, harnessing results from dynamical models in the literature. Two aircraft types are considered, a B737-300 (twin turbofan), taken as representative of short-range aircraft, and a B747-400, taken as representative of long-range aircraft. Airport and meteorological parameters are assigned values as holding in the case of Manchester Airport, UK, during a fortnight in May 1999 (prior to the opening of a second runway there). The airport operated at a capacity of about 45 aircraft movements per hour in the peak morning period, with frequencies in the middle of the day being about half this. Aircraft of maximum takeoff weight more than 120 tons accounted for some 6% of all movements. The simulations predict mean NO_x concentrations of maximum 3 ug per cubic meter at the center of the runway arising because of the vortex-mediated transport (as expressed on conversion of all NO to NO₂), with concentrations on the order of 1 ug per cubic meter arising 0.5 km laterally from the runway.

Graham, J. A. H. and Phillips, W. R.

"REYNOLDS STRESS AND VELOCITY MEASUREMENTS IN A TURBULENT TRAILING VORTEX"

TN-75-1, Apr. 1975, McGill Univ., Montreal, Canada

The results of a series of experiments conducted in a circular blower wind tunnel on a turbulent trailing vortex of Reynolds number $\Gamma/\nu = 57000$ are given. The results include the rotational and axial velocity components and the complete Reynolds stress tensor, for five cases of axial momentum, two jets, two wakes and a case of zero momentum increment. All measurements were made with a hot wire anemometer linked to an on-line digital computer. Results are given at three downstream locations, $x/c = 45, 78$ and 109 where c is the average chord width of the vortex generator.

Graham, J. A. H., Newman, B. G. and Phillips, W. R.

"TURBULENT TRAILING VORTEX WITH CENTRAL JET OR WAKE"

International Council of the Aeronautical Sciences Paper 74-40, Haifa, Israel, 1974

The concentrated trailing vortices from the wing of heavy aircraft contain significant rotational velocities which may persist for minutes. To reduce this time, the turbulence level in the core of the vortex may be increased by superimposing a longitudinal jet or wake. A series of experiments have been conducted in a circular wind tunnel with a trailing vortex along the center line. Jets or wakes of varying momentum were added to the center of the vortex. The mean velocity and the complete Reynolds stress tensor were measured at various azimuthal positions.

Graham, W. R.

"OPTIMISING WING LIFT DISTRIBUTION TO MINIMISE WAKE VORTEX HAZARD"

Aeronautical Journal, Vol. 106, August 2002, pp. 413-426

The aim of this work is to investigate how the wake vortex hazard generated by an aircraft can be reduced by modifying the wing lift distribution. The wake associated with a given lift distribution is simulated with a two-dimensional, inviscid 'vortex method'. A numerical optimization technique is used to guide the modifications so that a hazard measure, based on the rolling moment induced on a following aircraft encountering the wake, is minimized. The results show that a significant (~20-25%) reduction in hazard compared with conventional high-lift configurations can be achieved, via lift distributions that have a local minimum between the regions contributing to the flap and tip vortices. The counter-signed vorticity associated with this minimum appears to prevent the tip and flap vortices from merging, resulting in a safer wake. Furthermore, the hazard reduction is robust to variations in other features of the lift distribution and should thus be achievable in practice.

Graham, W. R.

"AN ASSESSMENT OF THE 2D VORTEX METHOD IN AIRCRAFT WAKE SIMULATION"

Aeronautical Journal, December 2001, pp. 653-666

Recent interest in aircraft vortex wakes has highlighted the need to identify appropriate algorithms for their simulation. The problem is not well-suited to grid-based techniques, due to the large domain and the need to avoid introducing artificial viscosity. A promising alternative is offered by Lagrangian formulations. This work aims to assess the usefulness of one such approach - the 2D vortex method - via comparison with experimental results. One in-house and two external (from DLR and ONERA) data sets are used. The results show generally good agreement in vortex locations and size, with the calculation performing best when initialized downstream of the strongly-three-dimensional trailing edge region. The neglect of viscosity can lead to some asymmetry in the vortex cores, but, even here, excellent agreement can be obtained when the field is integrated to give circulation (as a function of radius). The 2D vortex method is thus an accurate and efficient tool for wake vortex prediction.

Graham, W. R.

"EXPERIMENTAL ASSESSMENT OF THE EXTENDED BETZ METHOD FOR WAKE VORTEX PREDICTION"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, Trondheim, Norway, May 1996, pp. 9-1 TO 9-12

The extended Betz method, whereby wake vortex velocity predictions are obtained from a given wing lift distribution, is assessed by comparison with experimental results for wake cross-flow velocities behind a wing model with flaps. The required lift distributions are found from overall lift data and a lifting-line calculation, and the comparison is made for both clean and high-lift configurations. In each case it is found that the fundamental Betz assumption of effectively two-dimensional, inviscid flow in the wake is well supported, but that a proposed approximate invariant, the second moment of vorticity, is not conserved. In spite of this, the theoretical predictions for the single vortex shed by each half of the clean wing are found to be accurate. However, the multiple vortices arising from the wing in high-lift configuration are not as well predicted, and in this case the usefulness of the method seems to be restricted to providing estimates of the number of vortices, and their overall circulations.

Graham, W. R. and Bertenyi, T.

"MERGER OF CO-ROTATING VORTEX PAIRS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

The investigation has centered around wind tunnel experiments on co-rotating vortex pairs, generated by wings attached to the tunnel floor and side wall. Traverses with a single-tube yawmeter (effectively a five-hole probe) have been carried out over cross-flow planes at a range of downstream locations, yielding an extensive set of mean-flow data. These measurements have subsequently been analyzed to obtain the vortex circulations, core diameters and separations at each plane. For equal

circulations, the results show that each vortex retains an independent, essentially axisymmetric identity for most of the distance to merger. During this phase, core sizes increase and separation decreases. Merger then occurs over a short distance, after which a single axisymmetric vortex emerges. Unequal strength vortices behave similarly, in that the distance over which they merge is relatively short. However, notable differences in behaviour are observed; the weaker vortex is significantly distorted during the rotation before merger, and is then wrapped around the stronger as they combine. Lastly, the degree to which the merging process can be described as 'two-dimensional' is investigated via consideration of the theoretical 2D flow invariants. The results suggest that three-dimensional effects are not strong, and thus that vortex merging can be simulated using 2D flow computations.

Graham, W. R., Berteny, T. and David, L.

"THE EFFECT OF FLAP-END ADDITIONS ON AIRCRAFT TRAILING VORTICES"

Aeronautical Journal, February 2004, pp. 109-115

The influence of flap-end geometry modifications on the near-field wake behind a generic high-lift wing/flap configuration is investigated experimentally with a single-tube yawmeter. It is found that flap-end additions tend to split the concentrated area of streamwise vorticity shed by the flap into two less intense regions, associated with the tips of the flap and the addition. For shorter additions, these regions tend to roll up together, resulting in a slightly more diffusive flap vortex of almost unchanged circulation. For larger additions the outer region is captured by the tip vortex, which correspondingly gains in circulation at the expense of the flap vortex. In all cases, the vorticity centroid of the rolled-up wake is shifted outboard, and the overall circulation slightly increased. However, the associated lift increase implies a decrease in overall circulation at a given lift coefficient.

Graham, W. R., Park, S.-W. and Nickels, T. B.

"TRAILING VORTICES FROM A WING WITH A NOTCHED LIFT DISTRIBUTION"

AIAA Journal, Vol. 41, No. 9, September 2003, pp. 1835-1838

In this Note, a proof-of-concept tow-tank experiment on a novel, notched form of wing lift distribution has been described. The results confirm the fundamental conclusion of earlier numerical simulations, namely, that the flap and tip vortices shed by a wing with the novel distribution remain distinct and unmerged, unlike those associated with conventional high-lift distributions. This feature will lead to a reduced rolling moment on a follower aircraft encountering the wake and may also facilitate the development of rapidly growing instability modes. It is thus a promising avenue for wake hazard reduction and worthy of further work. This will consist of hazard reduction quantification and elucidation of the underlying mechanisms in more detail.

Graham, W. R., Park, S.-W. and Nickels, T. B.

"LIFT DISTRIBUTIONS FOR REDUCED WAKE VORTEX HAZARD"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

Since spacings, or 'separation distances', are imposed to protect the following aircraft from the trailing vortices of the leader, efforts have concentrated either on better characterization and assessment of the hazard, or on its reduction via modifications to the airframe configuration. The latter approach is particularly pertinent at present, with the launch of the A380 'super-jumbo' program. One promising method is to design a configuration that encourages early development of mutually-induced instabilities of the trailing vortex pair. An alternative approach is to aim to alleviate the wake vortex hazard in the absence of any instability. Here one would seek to distribute the shed vorticity in an optimal way, subject to the constraints of the aircraft's lift requirement. This approach is the subject of this paper. The method employed is 'steepest decent' optimization, which finds a minimum of a 'performance measure' with respect to the set of parameters that characterize the system. Here the performance measure used is an averaged rolling moment coefficient for a following aircraft, and the characterizing parameters are the coefficients of the lift distribution (represented as a Fourier series).

Grahame, W. E.

"A PRELIMINARY METHOD FOR THE PREDICTION OF MINIMUM INTERVAL TAKEOFF (MITO)"

TM 80-9.2/1, February 1980, Calspan Corp., Los Angeles, CA

Methodology to predict minimum interval takeoff (MITO) has been developed by Calspan from full-scale flight test wake vortex data and from analytical procedures which determine aircraft roll characteristics due to wake vorticity. The method has been applied to SAC-based aircraft, including the FB-111, KC-135, B-52 and B-1, which were 'flown' behind a 747 (E-4) aircraft to determine MITO time sequences. Appropriate expressions for circulation and vortex peak vorticity decay based on 747 flight test data were applied. From these expressions, values of vortex core radius were calculated and applied in a roll moment function to determine variations of the vortex-induced roll moment coefficient with time. Values of vortex-induced rolling moment as a function of time were calculated and compared against maximum roll capability to indicate 'safe' time intervals for MITO.

Graham-Rowe, D.

"VANQUISH THE VORTEX"

New Scientist, Vol. 173, Issue 2332, February 2002, p. 9

The swirling turbulence caused by jets taking off and landing can be a danger for planes in their wake. But a couple of rollers fixed to each wing could solve the problem. In a 2D simulation of air flowing across a square block, wake vortices formed as normal. But when two rollers along the back edge of the block rotated towards each other, they drew air into the space behind the block and the swirls straightened out, disappearing completely when the rollers rotated 50 per cent faster than the air flow. The researchers suggest you could install the rollers along the trailing edge of airplane wings to stop the

wake at its source, without increasing drag. But first they need to show that the trick would work in three dimensions.

Granger, R.

"STEADY THREE-DIMENSIONAL VORTEX FLOW"

J. Fluid Mech., Vol. 25, Part 3, July 1966, pp. 557-576.

A theory is developed for an incompressible fluid in a steady three-dimensional rotational flow. Solutions are obtained subject to the restriction of small perturbations and are determinant provided that the vorticity distribution along the axis of rotation is known. Effects of viscosity are included.

Grant, I., Mo, M., Pan, X., Parkin, P., Powell J. and Hurst, D.

"COMPUTERISED ANIMATION OF PIV MEASUREMENTS AND LASER SHEET VISUALISATION IN THE WAKE OF A PASSENGER AIRCRAFT MODEL IN A LARGE, LOW-SPEED, WIND-TUNNEL"

8th International Symposium on Flow Visualization, Sorrento, Italy, 1998, pp. 277.1-277.

A particle image velocimetry (PIV) and laser sheet visualization (LSV) study of the flow behind a 1/12.81 scale model of a representative passenger aircraft was undertaken in a 10 ft. by 12 ft. closed return wind tunnel. Measurements were made in planes, normal to mean flow, at various downstream positions, for different model configurations. The data images were analyzed to extract raw velocity vectors after which the data were processed to obtain velocity measurements on a regular grid. From this information vorticity, divergence and cross flow energy were calculated. In addition, animations of the data were assembled to show both typical local temporal flow variation at one downstream plane and flow variation with downstream distance from the model wing tip. These procedures are discussed and examples of the data sets presented.

Grant, I., Mo, M., Pan, X., Parkin, P., Powell, J. and Hurst, D.

"A PIV AND LSV STUDY IN THE WAKE OF AN AIRCRAFT MODEL"

Journal of the Visualization, Vol. 2, No. 1, July 1999

An experimental investigation was undertaken of the wake aerodynamics of a 1/12.81 model of a commercial passenger aircraft. The tests were undertaken in the 3.05 m by 3.66 m working section of a closed-return wind-tunnel. The program made use of laser sheet visualization (LSV) and particle image velocimetry (PIV) in planes, normal to the mean flow, to obtain images of flow-following, seed particles. The images were processed to obtain raw velocity vectors, flow divergence, vorticity, cross-flow energy and high-quality visualizations. Image sequences obtained under identical incident flow conditions were used to conceptualize the variability of principal wake features such as regions of fluid of high vorticity.

Grant, I., Mo, M., Pan, X., Parkin, P., Powell, J., Reinecke, H., Shuang, K., Coton, F. and Lee, D.

"AN EXPERIMENTAL AND NUMERICAL STUDY OF THE VORTEX FILAMENTS IN THE WAKE OF AN OPERATIONAL, HORIZONTAL-AXIS, WIND TUBINE"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 85, 2000, pp. 177-189.

The paper describes a wind-tunnel study of the wake dynamics of an operational, horizontal-axis wind turbine. The behavior of the vorticity trailing from the turbine blade tips and the effect of interference on wake development were considered. Laser sheet visualization techniques were used to measure the trajectories of the trailing vorticity under various conditions of turbine yaw and blade azimuth. Selected results obtained in the experimental study were compared with the predictions of a prescribed wake model and are being used in the further development of the method.

Grasso, F. and Pirozzoli, S.

"SHOCK-WAVE-VORTEX INTERACTIONS: SHOCK AND VORTEX DEFORMATIONS, AND SOUND PRODUCTION"

Theoretical and Computational Fluid Dynamics, Vol. 13, 2000, pp. 421-45.

In this paper we study the interaction of a shock wave with a cylindrical vortex. The objective of the study is to characterize the shock and vortex deformations and the mechanism of sound generation. The approach relies on the solution of the two-dimensional Euler equations by means of a high order finite volume weighted-ENO scheme. To provide some guidance into the analysis, we have also developed an acoustic analogy of the problem by formulating a wave equation for the pressure disturbance that is solved analytically by means of Green's functions. A systematic study has been conducted by investigating the effects of vortex intensity and shock strength. Specifically, we have determined the dependence of shock distortion and vortex compression, and its subsequent nutation upon shock and vortex strengths. The acoustic field generated through shock-vortex interactions has been found to evolve in three stages and to exhibit a three sound quadrupolar directivity. In the early stages of the interaction the sound generated due to shock distortion shows a dipolar character, which then changes to a quadrupolar one due to a restoring mechanism that acts during the interaction of the shock with the rear part of the vortex. In the third stage secondary sounds are formed, which also show a quadrupolar directivity. The acoustic analogy applied to weak shock-vortex interactions also confirms the numerically predicted sound generation mechanism.

Gray, R. B., McMahon, H. M., Shenoy, K. R. and Hammer, M. L.

"SURFACE PRESSURE MEASUREMENTS AT TWO TIPS OF A MODEL HELICOPTER ROTOR IN HOVER"

NASA Contractor Report 3281, May 1980, Georgia Institute of Technology, Atlanta, GA.

Blade-tip surface pressure distribution data for a single-bladed, hovering, model helicopter rotor with two tip shapes are compared. The rotor had a constant-chord, untwisted blade with a square, flat tip and the pressure distributions on this blade are compared with those measured on the same blade with a half-body of revolution tip. Pressure measurements were made on each blade along the chordwise direction at six radial stations outboard of the 94 percent blade radius. Data on each blade were taken at blade collective pitch angles of 0, 6.18, and 11.4 degrees. The Reynolds number based on tip speed and blade chord was 736,000 and the tip Mach number was 0.25. For a blade pitch angle of 0 degrees, a small difference in pressure distribution between the two blades occurred very near the tip. For the pitch angles of 6.18 and 11.4 degrees, the chordwise pressure distributions at the 94 percent radius station were essentially unaffected by the tip shapes investigated. The largest differences in the pressure distributions were near the tip and toward the trailing edge, and were associated with the rearward sweep of the tip vortices over the upper surfaces of the blades. The extent of the affected surface areas was greater for the larger blade pitch angles in each case. However, for the same blade pitch angle, the affected surface area was smaller for the blade with the body-of-revolution tip since the path of its tip vortex was outboard of that of the blade with the square, flat tip.

Green, M. W.

"MEASUREMENT OF THE MOMENTS OF INERTIA OF FULL SCALE AIRPLANES"

NACA TN-265, January 1927, Langley Aeronautical Lab., Langley Field, VA.

This paper contains a description of the method of measuring the moments of inertia of full-scale airplanes as practiced by the National Advisory Committee for Aeronautics at the Langley Laboratory. The method, while not at all new, is published for information and guidance of others who may desire to make similar measurements. The paper includes as an appendix the computations for the moments of inertia of the O-2 airplane.

Green, R. B., Doolan, C. J. and Cannon, R. M.

"MEASUREMENTS OF THE ORTHOGONAL BLADE-VORTEX INTERACTION USING A PARTICLE IMAGE VELOCIMETRY TECHNIQUE"

Experiments in Fluids, Vol. 29, 2000, pp. 369-379.

This paper describes the results of application of a particle image velocimetry (PIV) technique to an orthogonal blade-vortex interaction experiment. To help resolve the problem of vortex meander during the tests, two PIV systems were used, which produced two velocity vector maps closely separated in time. During the PIV analysis an image-based vector validation scheme was used, which was shown to reduce significantly the number of wild vectors reaching the vector map. Preliminary results from the tests showed that, close to the blade, a significant radial outflow was superimposed on the vortex flow field. The radial flow is thought to be due to the dispersion of the vortex axial core flow during vortex cutting, which distorts the vortex flow field and enlarges the vortex. Further away from the blade, no significant radial flow was detected and the vortex remained undisturbed.

Green, R. B., Gillies, E. A. and Brown, R. E.

"THE FLOW FIELD AROUND A ROTOR IN AXIAL DESCENT"

J. Fluid Mech., Vol. 534, 2005, pp. 237-261

Measurements of the flow field around a model rotor descending axially into its own vortex wake have been performed using particle image velocimetry (PIV). At low descent rates, the expected cylindrical down-flow structure below the rotor is observed. At slightly higher descent rate, the flow enters the so-called vortex ring state (VRS) where the vorticity from the rotor accumulates into a toroidal structure near the rotor tips, and a large recirculation zone forms above the rotor disk. In the VRS, the flow below the rotor shows a significant upwards component, with a small up-flow zone penetrating right up to the rotor disk. Measurements show there to be a range of descent rates just before the onset of the VRS over which the flow may be interpreted to be in an incipient VRS condition. In this range, analyses of individual PIV measurements indicate that the flow near the rotor intermittently switches between the down-flow topology found at lower descent rates and the flow topology found in the fully developed VRS. The frequency of excursions of the flow into the VRS topology increases as the descent rate of the rotor is increased until, at high enough descent rate, the flow remains locked within its toroidal state.

Green, S. I.

"CORRELATING SINGLE PHASE FLOW MEASUREMENTS WITH OBSERVATIONS OF TRAILING VORTEX CAVITATION"

J. Fluids Engineering, Vol. 113, March 1991, pp. 125-129

The single phase and cavitating tip vortex shed by a NACA 66-209 rectangular planform, rounded tip hydrofoil has been studied. Single-phase measurements of instantaneous flow velocity were made by taking double-pulsed holograms of microbubbles moving in and around the vortex core. The tailored air bubble technique of Ooi and Acosta (1983) was employed to measure both the mean and fluctuating single phase vortex core static pressure. Cavitation inception was determined visually. The flow in the vortex core is highly unsteady; the rms axial velocity fluctuation can be as high as 0.2 times the freestream velocity. Core pressure fluctuations greater than the freestream dynamic pressure have been observed. These fluctuations are commensurate with the axial velocity unsteadiness. Cavitation inception in saturated water occurs at mean core pressures above the vapor pressure. However, the pressure fluctuations are certainly substantial enough to account for these elevated inception indices. The rapid establishment of fully developed trailing vortex cavitation when the cavitation number is reduced below inception is attributable to the small variation in mean core pressure with downstream distance. The inception index increases substantially with dissolved air content. The cause of this dependence is not presently known.

Green, S. I.

"WING TIP VORTICES"

Fluid Vortices, 1st ed., Kluwer Academic Publishers, The Netherlands, 1995, pp. 427-470

One of the most conspicuous features of an airplane flying at high altitude is its white contrails. These contrails, which are formed by the condensation of engine exhaust water vapor, clearly delineate the location of the wing tip vortices. This chapter aims to explain the origin of tip vortices and review their technological relevance. The chapter then summarizes lifting line theory, the simplest finite wing theory, and synthesizes our knowledge of tip vortex behavior.

Green, S. I. and Acosta, A. J.

"UNSTEADY FLOW IN TRAILING VORTICES"

J. Fluid Mech., Vol. 227, June 1991, pp. 107-134

The instantaneous velocity distribution in trailing vortices generated by lifting hydrofoils has been measured. Two different rectangular planform hydrofoils with small aspect ratios were tested. Double-pulsed holography of injected microbubbles, which act much as Lagrangian flow tracers, was used to determine instantaneous axial and tangential velocities. Measurements were made at various free-stream velocities, angles of attack, and downstream distances. The vortex core mean axial velocity is consistently greater than the free-stream velocity near the hydrofoil trailing edge, and decreases with downstream distance. The mean axial velocity is strongly Reynolds-number dependent. Axial flow in the trailing vortex is highly unsteady for all the flow conditions studied; peak-to-peak fluctuations on the centerline as large as the free-stream velocity have been observed. Certain unusual structures of the vortex core - regions in which the flow direction quickly diverges from the free-stream direction, and then equally quickly recovers - have been labelled 'vortex kinks'.

Green, S. I. and Duan, S. Z.

"THE DUCTED TIP -- A HYDROFOIL TIP GEOMETRY WITH SUPERIOR CAVITATION PERFORMANCE"

Journal of Fluids Engineering, Vol. 117, December 1995, pp. 665-672.

A novel hydrofoil design, consisting of a small diameter flow-through duct affixed to the tip, has been studied. The tip vortex cavitation inception index of this hydrofoil geometry is about a factor of 2 lower than that of a conventional rounded hydrofoil tip. This inception improvement comes with little associated performance penalty. For angles of attack greater than 8 deg the non-cavitating lift-drag ratio is superior to that of an induced hydrofoil of equal span, although with lower wing loadings the hydrofoil performance is diminished by application of the ducted tip. The ducted tip is effective at reducing the tip vortex inception index because, in contrast with the rounded tip, for which vorticity in the Trefftz plane is confined to a line, the ducted tip shed vorticity at the trailing edge is distributed over a line and circle. Distributing the vorticity in this fashion causes the trailing vortex to roll up less tightly, and hence have a higher core pressure and lower cavitation convection index than a conventional hydrofoil tip. It is also suspected that the interaction at the microscale level between the

flow through the duct, and the flow around it, makes the vortex core size larger, and therefore cavitation inception index smaller. The ducted tip design has many potential marine applications, including to ship and submarine propellers, submarine control fins, and ship rudders.

Green, S. I., editor

"FLUID VORTICES"

1st ed., Kluwer Academic Publishers, The Netherlands, 1995

Fluid Vortices is an advanced, graduate-level, textbook covering all salient flows in which fluid vortices play a significant role. Topics addressed include fundamental vortex flows (mixing layer vortices, vortex rings, wake vortices, vortex stability, etc.), industrial and environmental vortex flows (aero-propulsion system vortices, vortex-structure interaction, atmospheric vortices, computational methods with vortices, etc.), and multiphase vortex flows (free-surface effects, vortex cavitation, and bubble and particle interaction, with vortices).

Greenberg, M. D. and Kaskel, A. L.

"INVISCID FLOW FIELD INDUCED BY A ROTOR IN GROUND EFFECT"

NASA CR-1027, May 1968, Therm Advanced Research Inc., Ithaca, NY

The inviscid flow field induced by a rotor in ground effect is calculated based upon an actuator disk model of the rotor, for the case of a constant circulation distribution over the blade radius. The governing nonlinear integral equations are solved by a systematic iterative scheme which is like the Newton-Raphson method for the solution of nonlinear algebraic equations. Numerical results are presented for both the ground-effect case and the out-of-ground effect limit.

Greenblatt, D.

"MANAGEMENT OF VORTICES TRAILING FLAPPED WINGS VIA SEPARATION CONTROL"

AIAA Paper No. 2005-0061, Reno, NV, January 2005

A pilot study was conducted on a flapped semi-span model to investigate the concept and viability of near-wake vortex management via separation control. Passive control was achieved by means of a simple fairing and active control was achieved via zero mass-flux blowing slots. Vortex sheet strength, estimated by integrating surface pressure ports, was used to predict vortex characteristics by means of inviscid rollup relations. Furthermore, vortices trailing the flaps were mapped using a seven-hole probe. Separation control was found to have a marked effect on vortex location, strength, tangential velocity, axial velocity, and size over a wide range of angles of attack and control conditions. In general, the vortex trends were well predicted by the inviscid rollup relations. Manipulation of the separated flow near the flap edges exerted significant control over both outboard and inboard edge vortices while producing negligible lift excursions. Dynamic separation and attachment control was found to be an

effective means for dynamically perturbing the vortex from arbitrarily long wavelengths down to wavelengths less than a typical wingspan. In summary, separation control has the potential for application to time-independent or time-dependent wake alleviation schemes, where the latter can be deployed to minimize adverse effects on ride-quality and dynamic structural loading.

Greenblatt, D.

"CONTROL OF FLAP VORTICES"

45th Israel Annual Conf. on Aerospace Science, Haifa, Israel, February 2005.

A wind tunnel investigation was carried out on a semi-span wing model to assess the feasibility of controlling vortices emanating from outboard flaps and tip-flaps by actively varying the degree of boundary layer separation. Separation was varied by means of perturbations produced from segmented zero-efflux oscillatory blowing slots, while estimates of span loadings and vortex sheet strengths were obtained by integrating wing surface pressures. These estimates were used as input to inviscid rollup relations as a means of predicting changes to the vortex characteristics resulting from the perturbations. Surveys of flow in the wake of the outboard and tip-flaps were made using a seven-hole probe, from which the vortex characteristics were directly deduced. Varying the degree of separation had a marked effect on vortex location, strength, tangential velocity, axial velocity, and size for both outboard and tip-flaps. Qualitative changes in vortex characteristics were well predicted by the inviscid rollup relations, while the failure to account for viscosity was presumed to be the main reason for observed discrepancies. Introducing perturbations near the outboard flap-edges or on the tip-flap exerted significant control over vortices while producing negligible lift excursions.

Greenblatt, D.

"FLUIDIC CONTROL OF A WING TIP VORTEX"

AIAA Journal, Vol. 50, No. 2, February 2012, pp. 375-386.

A novel technique of active wing tip vortex control was studied in a wind tunnel by deflecting a flap mounted at the tip of a semispan NACA 0015 wing model and then modifying the shear layer above the flap by means of zero mass-flux, fluidic perturbations. Primary data acquired included surface pressure measurements and particle image velocimetry of the flap region and of the vortex downstream of the wing tip. The shear layer above the flap was particularly responsive to fluidic perturbations, requiring small relative momentum to produce large changes to the layer and consequently the vortex. However, integrated surface pressures showed that deflection of the shear layer, and even eliminating separation completely, has a relatively small effect on the overall aerodynamic loads. Deflection of the shear layer had the effect of moving the vortex outboard and changing the axial velocity at the vortex center from wake-like to jet-like flow. The spanwise deflection of the vortex centroids correlated with the nature of the loading near the wing tip: forward loading corresponded to inboard vortex movement; aft loading corresponded to outboard vortex movement. Variation of the vortex axial velocity was described using

the mechanical energy equation where changes from wake-like to jet-like flow were, respectively, comparable to the magnitude of the freestream velocity.

Greenblatt, D.

"MANAGING FLAP VORTICES VIA SEPARATION CONTROL"

AIAA Journal, Vol. 44, No. 11, November 2006, pp. 2755-2764

A pilot study was conducted on a flapped semispan model to investigate the concept and viability of near-wake vortex management by means of boundary layer separation control. Passive control was achieved using a simple fairing and active control was achieved via zero mass-flux blowing slots. Vortex sheet strength, estimated by integrating surface pressures, was used to predict vortex characteristics based on inviscid roll-up relations and vortices trailing the flaps were mapped using a seven-hole probe. Separation control was found to have a marked effect on vortex location, strength, tangential velocity, axial velocity, and size over a wide range of angles of attack and control conditions. In general, the vortex trends were well predicted by the inviscid roll-up relations. Manipulation of the separated flow near the flap edges exerted significant control over either outboard or inboard edge vortices while producing small lift and moment excursions. In summary, separation control has the potential for application to time-independent or time-dependent wake alleviation schemes, where the latter can be deployed to minimize adverse effects on ride-quality and dynamic structural loading.

Greenblatt, D., Pack-Melton, L. G., Yao, C.-S. and Harris, J.

"ACTIVE CONTROL OF A WING TIP VORTEX"

AIAA Paper No. 2005-4851, Toronto, Canada, June 2005.

Active control of a wing tip vortex was studied by deflecting a flap mounted at the tip of a semi-span wind tunnel model and then varying the degree of boundary layer separation by means of zero mass-flux perturbations. Qualitative trends were predicted based on well-known theoretical approaches. Static and dynamic pressure measurements were made to assess the loads on the wing and particle image velocimetry was used to map the flow above the flap and in the wake. Varying the degree of flow separation, and even eliminating separation completely on the tip-flap, was seen to have a small effect on the overall aerodynamic loads. Nevertheless, the flow above the flap was also seen to be amenable to separation control, requiring small control momentum to produce large changes to the vortex. Reduction of the flap-separated region eliminated the axial velocity deficit and ultimately generated an axial velocity surplus near the center of the vortex. This was accompanied by significant increases in streamwise vorticity. Separation control was found to be well suited to dynamically perturbing the trailing vortex from arbitrarily long wavelengths to wavelengths very much shorter than the wingspan. Dynamic perturbation of the vortex at length-scales less than the wing chord were achieved at the separation control frequencies. Longer wavelengths were perturbed using dynamic separation and attachment control.

Greenblatt, D., Vey, S., Paschereit, O. C. and Meyer, R.

"FLAP VORTEX MANAGEMENT USING ACTIVE GURNEY FLAPS"

AIAA Journal, Vol. 47, No. 12, December 2009, pp. 2845-2856.

An experimental study was conducted to assess the applicability of limited-span Gurney flaps for altering the flap-edge vortex characteristics of a swept constant-chord half-model with a commercial aircraft airfoil and high-lift system (slat and flap). The strategy employed was based on the well-known vortex roll-up relations between the span loading and the wake that were extended and modified to include configurations with flapped wings. Phase I of the study involved the testing of static Gurney flaps mounted at the trailing edge and flap edge, in which different flap heights and fractions of flap span were evaluated. Data acquisition included particle image velocimetry measurements downstream of the flap edge, six-component load measurements, and surface pressure measurement on the main element and in the flap-edge region. The Gurney flaps produced significant variation of the vortex centroids, up to 5.39% of the semispan (13.1% of chord), with corresponding small changes to lift and drag coefficients. Phase II of the study, involved the evaluation of dynamically deployed Gurney flaps, in which phase-averaged particle image velocimetry measurements were made of the vortex trailing the flap. This was motivated by the desire to periodically perturb the vortex centroids, with a view to exciting wake instabilities and thus triggering a faster decay. When driving the Gurney flap and hence perturbing the vortices at wavelengths shorter or longer than the wingspan, the authority over the vortex centroids did not materially change.

Greenblatt, D., Yao, C.-S., Vey, S., Paschereit, O. C. and Meyer, R.

"ACTIVE MANAGEMENT OF FLAP-EDGE TRAILING VORTICES"

AIAA Paper No. 2008-4186, June 2008, Seattle, WA.

The vortex hazard produced by large airliners and increasingly larger airliners entering service, combined with projected rapid increases in the demand for air transportation, is expected to act as a major impediment to increased air traffic capacity. Significant reduction in the vortex hazard is possible, however, by employing active vortex alleviation techniques that reduce the wake severity by dynamically modifying its vortex characteristics, providing that the techniques do not degrade performance or compromise safety and ride quality. A series of experiments were performed. The investigations demonstrated the basic mechanism for managing trailing vortices using retrofitted devices that are decoupled from conventional control surfaces. The basic premise for managing vortices advanced here is rooted in the erstwhile forgotten hypothesis of Albert Betz, as extended and verified ingeniously by Donaldson and his collaborators. Using these devices, vortices may be perturbed at arbitrarily long wavelengths down to wavelengths less than a typical airliner wingspan and the oscillatory loads on the wings, and hence the vehicle, are small. Significant flexibility in the specific device has been demonstrated using local passive and active separation control as well as local circulation control via Gurney flaps. The authors believed that this method will have significant appeal from an industry perspective due to its retrofit potential with little to no impact on cruise (devices tucked away in the cove or retracted); low operating power requirements; small lift oscillations when

deployed in a time-dependent manner; and significant flexibility with respect to the specific devices selected.

Greene, G. C.

"AN ENTROPY METHOD FOR INDUCED DRAG MINIMIZATION"

SAE Paper 89-2344, September 1989, Anaheim, CA.

A fundamentally new approach to the aircraft minimum induced drag problem is presented. The method, a 'viscous lifting line' is based on the minimum entropy production principle and does not require the planar wake assumption. An approximate, closed form solution is obtained for several wing configurations including a comparison of wing extension, winglets, and in-plane wing sweep, with and without a constraint on wing-root bending moment. Like the classical lifting-line theory, this theory predicts that induced drag is proportional to the square of the lift coefficient and inversely proportional to the wing aspect ratio. Unlike the classical theory, it predicts that induced drag is Reynolds number dependent and that the optimum spanwise circulation distribution is non-elliptic.

Greene, G. C.

"FAA'S RESEARCH STRATEGY"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Wake turbulence is an international concern that currently limits airport capacity and constrains the implementation of new technologies and procedures which might increase airport efficiency. Therefore, wake turbulence research must be a significant consideration in any plan addressing the capacity of the air traffic system. Recently, both the FAA and the Boeing Co. released plans for significantly enhancing air traffic system capacity. This talk addressed the FAA's research strategy for ensuring that wake turbulence considerations do not limit the implementation of these planned enhancements. Specific topics included near term research on closely spaced parallel runway operations, evolution of NASA AVOSS technology for operational use, and international cooperation in wake turbulence research.

Greene, G. C.

"CURRENT STATUS AND APPLICATION OF HAZARD DEFINITION TECHNOLOGY"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 342-350

This talk discusses the preliminary application of wake vortex hazard technologies to evaluate current aircraft separation standards. The purpose of the current research is to evaluate the state of technology for operational use and identify promising areas for future research. The study was based

on analysis tools for 1) estimating the initial wake strength, 2) estimating the effects of the atmosphere on the wake, and 3) estimating the effects of the wake on an encountering aircraft. Using a specified definition of an acceptable vortex encounter, minimum aircraft separation times were determined. The results were used as input to an optimizer for determining an optimum set of aircraft categories which would maximize a simple model of airport capacity. For a given maximum level of wake hazard exposure, it was found that optimizing aircraft categories by wing span, rather than weight, provided a modest increase in airport capacity. It was also found that categories for maximum airport capacity depended on the traffic mix and therefore optimum standards would be airport dependent.

Greene, G. C.

"WAKE VORTEX RESEARCH - CURRENT ISSUES AND FUTURE DIRECTION"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 39-40.

This paper will briefly review past research leading up to some of the current issues in wake vortex research. Recent US experience in changing aircraft separation standards will be used to highlight some of the current issues. One view of future research requirements will be presented.

Greene, G. C.

"EFFECTS OF WEATHER ON AIRCRAFT WAKE TURBULENCE EXPERIENCED DURING CRUISE FLIGHT"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

Weather effects on aircraft wake turbulence in the terminal area are a current topic of international research. Due to recent reductions in vertical aircraft spacing over the north Atlantic Ocean, there is increasing international interest in the effects of wake turbulence during cruise operations. This paper presents an analytical study of the effects of weather and aircraft size on the potential for wake turbulence in cruise. A simple model of wake motion and decay is used to estimate the effects of winds, atmospheric turbulence, and temperature lapse rate on the maximum distance which a wake might descend. An estimate is also provided as to whether the wake remains coherent or descends as a series of crude rings due to the Crow Instability. The wing span of the generating aircraft is shown to be a critical parameter in addition to the weather.

Greene, G. C.

"WAKE VORTEX ALLEVIATION"

AIAA Paper No. 1981-0798, Atlantic City, NJ, May 1981.

This paper describes some of the National Aeronautics and Space Administration's (NASA's) recent and current research on aerodynamic techniques for minimizing the aircraft trailing vortex hazard. The potential benefits and operating problems of the more promising concepts are discussed. Recent

flight-test results are presented which show that essentially total vortex alleviation can be achieved at a 3 nautical mile separation distance by oscillating the aircraft's lateral-control surfaces. While not operationally practical, these results suggest that it may be possible to minimize the wake hazard by exciting longitudinal instabilities.

Greene, G. C.

"AN APPROXIMATE MODEL OF VORTEX DECAY IN THE ATMOSPHERE"

Journal of Aircraft, Vol. 23, No. 7, July 1986, pp. 566-573.

An approximate analysis of atmospheric effects on wake vortex motion and decay is presented. The effect of density stratification, turbulence, and Reynolds number are combined in a single model so that the relative importance of different parameters can be estimated. Predicted wake motion is shown to be in good agreement with limited data from ground facility and flight test measurements taken under low-turbulence conditions. Wake decay was found to depend strongly on both density stratifications and turbulence. For typical levels of turbulence, wake decay was found to result from the Crow instability except under strongly stratified conditions.

Greene, G. C.

"WAKE VORTEX MINIMIZATION"

Potential Impacts of Advanced Aerodynamic Technology on Air Transportation System Productivity, NASA TM-109154, edited by D. Bushnell, NASA Langley Research Center, Hampton, VA, September 1994, p. 94

A review was given of wake vortex minimization efforts. Considerable research was undertaken in the 1970's to help reduce the adverse effects of an airplane wake, but the assumptions in this early research were that maximum vortex velocities were associated with the vortex hazard without the concern for the whole vorticity throughout the flow field. Since then, an improved understanding has merged to show the powerful effect inboard vortices have on the primary (tip) vortex, and the importance of atmospheric coupling.

Greene, G. C.

"HISTORY OF WAKE VORTEX RESEARCH: PROBLEMS AND ACCOMPLISHMENTS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 23-32

This talk presents a history of wake vortex research with emphasis on significant problems and accomplishments. Early lessons in wake physics from wake alleviation research conducted in wind

tunnels and in-flight tests are discussed. The effects of atmospheric conditions and test techniques on the reliability of existing data are emphasized. Significant events, such as the British Vortex Incident Reporting System, which have had a long-term effect on wake vortex research are described. Remaining questions and challenges for implementing an operational wake vortex system are summarized. Although much has been learned through technical research, the primary challenges are to solve the operational wake vortex issues which face the international community.

Greene, G. C.

"A380 INTERNATIONAL WAKE VORTEX WORKING GROUP OVERVIEW"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

The Airbus A380 will be larger and heavier than existing commercial air transport aircraft. To maintain the operational safety of other aircraft, air traffic service providers/national aviation safety regulators need assurance of the adequacy of the separation standards to be applied to the A380. Due to the increase in mass/size of the A380 compared to current aircraft types, a special study was deemed necessary to investigate the A380's wake vortex characteristics and to compare them with other existing types of aircraft. To accomplish this study and ensure that the results would be applied internationally, a Steering Group was established with members from CJAA, Eurocontrol, FAA, ICAO Secretariat, and Airbus. This Steering Group forms appropriate Working Groups as required, consisting of experts and specialists in appropriate areas. At the initial meeting, a Technical Working Group was formed to accomplish the more scientific aspects of this effort. This talk provides an overview of the composition and responsibilities of the Steering Group and Technical Working Group and introduces two additional talks, which address the approaches to be taken in assessing the A380 wake turbulence risk.

Greene, G. C., Dunham, Jr., R. E., Burnham, D. C., Hallock, J. N. and Rossow, V. J.

"WAKE VORTEX RESEARCH LESSONS LEARNED"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 2-1 - 2-13

During the 1970's and the early 1980's, the FAA and NASA conducted extensive wake vortex research programs with the goal of safely increasing airport capacity. The FAA program focused on developing an extensive data base and the technology for predicting and/or detecting the presence of a vortex and advising controllers when aircraft separations could be safely reduced. The NASA program emphasized reducing the wake hazard through changes to the aerodynamic characteristics of the aircraft. Both programs made significant technical progress even though neither program resulted in an implementable solution. Current research has the same goal and many of the same challenges as the earlier research. This paper discusses the most important lessons learned from prior research by both

the FAA and NASA and, in particular, how prior research has shaped the issues, requirements, and constraints which will affect any proposed solution.

Greene, G. C., Lamar, J. E. and Kubendran, L. R.

"AIRCRAFT VORTICES - JUNCTURE, WING, AND WAKE"

AIAA Paper No. 1988-3742, Cincinnati, OH, July 1988.

Many real aircraft flows contain regions of three-dimensional separation with vortices. This paper presents selected results for three representative flows: juncture vortex, lifting-wing vortex, and wake vortex. Due to the difficulty of studying vortices, flow visualization was used as a primary research tool. Vortices are found to depend in subtle ways on details of the configuration, Reynolds number, or the environment. Examples showing the effect of filleting on the juncture flow, Reynolds number on the wing flow, and density gradients on the wake flow are presented.

Greene, G. C., Williams, R. and Rees, F.

"PROJECT SOCRATES: USE OF LASER BEAMS TO SENSE ACOUSTIC EMANATIONS FROM AIRCRAFT WAKE VORTICES"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

Development of a new technology that uses low-power laser beams to detect acoustic energy emanating from aircraft wake vortices is being sponsored by the Federal Aviation Administration and the National Aeronautics and Space Administration. A system based on this technology was used to monitor aircraft landings at JFK International Airport. Acoustic signals from wake vortices recorded by the system and the results of their analysis are described.

Greenhalgh, S.

"LIFT ENHANCEMENT DEVICE"

US Patent 5,226,618, July 1993

A lift enhancing device for an inextensible, membranous wing is disclosed. The device comprises the 'forced' reattachment of a section of the trailing edge back to the trailing edge so that a warp is introduced therein. The section is reattached with flexible tape to allow oscillation of the section, and increased lift from the wing, at prescribed airspeeds.

Greenhut, G. K. and Mastrantonio, G.

"TURBULENCE KINETIC ENERGY BUDGET PROFILES DERIVED FROM DOPPLER SODAR MEASUREMENTS"

Journal of Applied Meteorology, Vol. 28, February 1989, pp. 99-106.

Doppler sodar wind measurements made in light wind conditions in September 1979 near a power plant in Turbigo, Italy, are used to derive terms in the turbulence kinetic energy (TKE) budget. Measurements on five days are grouped into two classes: fair-weather conditions and boundary layer interaction with subsiding air. Profiles of $(\sigma w^3)/z$ are used to obtain the surface heat flux and the vertical velocity scaling parameter, as well as the buoyancy production term in the TKE budget. The vertical transport of TKE is derived from the profiles of the averaged w' cubed. The horizontal components are approximated using a parameterization based on the data of Lenschow et al. Dissipation in the TKE budget is obtained from a spectral analysis of the Doppler sodar data in the inertial subrange. The resulting TKE budget profiles for the two classes are compared with budgets obtained previously, using several different methods.

Greenwell, D. I.

"PITFALLS IN THE INTERPRETATION OF DELTA WING FLOW VISUALIZATION"

RTO-MP-069, March 2003, NATO Research and Technology Organization, Neuilly-Sue-Seine Cedex, France.

This paper illustrates some pitfalls in the interpretation of flow visualization images of delta wing leading-edge vortices. Numerical simulations of tracer particle trajectories in around straight and helical vortices are presented, representing unburst and burst delta wing vortices respectively. For straight vortices, the appearance of the 'smoke-ring' effect in wind tunnel testing is analyzed, and shown to be unrelated to the size or presence of a viscous inner core in the vortex. The role of the swirl-induced radial pressure gradient in the vortex centerline trace seen in water tunnels is demonstrated. For helical (burst) vortices, the crossflow topology visualized with upstream tracer injection is shown to depend on the vortex core size and the helix pitch. Typical vortex helices are close to a flow regime which can produce visualized flow structures resembling axisymmetric bubble breakdowns. It is postulated that the intermittent open-ended bubble burst seen in delta wing vortices is in fact an artifact of the tracer flow visualization technique, as transient disturbances temporarily reduce the pitch of the fundamental helical burst structure.

Greenwell, D. I.

"PITFALLS IN THE INTERPRETATION OF DELTA WING FLOW VISUALIZATION"

RTO AVT Symposium on Advanced Flow Management: Part A -- Vortex Flows and High Angle of Attack for Military Vehicles, May 2001, Loen, Norway.

This paper illustrates some pitfalls in the interpretation of flow visualization images of delta wing leading-edge vortices. Numerical simulations of tracer particle trajectories in around straight and helical vortices are presented, representing unburst and burst delta wing vortices respectively. For straight vortices, the appearance of the 'smoke-ring' effect in wind tunnel testing is analyzed, and shown to be unrelated to the size or presence of a viscous inner core in the vortex. The role of the

swirl-induced radial pressure gradient in the vortex centerline trace seen in water tunnels is demonstrated. For helical (burst) vortices, the crossflow topology visualized with upstream tracer injection is shown to depend on the vortex core size and the helix pitch. Typical vortex helices are close to a flow regime which can produce visualized flow structures resembling axisymmetric bubble breakdowns. It is postulated that the intermittent open-ended bubble burst seen in delta wing vortices is in fact an artifact of the tracer flow visualization technique, as transient disturbances temporarily reduce the pitch of the fundamental helical burst structure.

Greenwell, D. I. and Gursul, I.

"EFFECT OF TRACER PARTICLE CHARACTERISTICS ON VISUALISATION OF DELTA WING VORTICES"

9th International Symposium on Flow Visualization, Paper No. 111, 2000, pp. 111-1-111-10

Preliminary investigations of the effect of tracer particle characteristics on flow visualization in a steady delta wing leading-edge vortex are presented, using both 3D simulations of particle trajectories and a simplified analysis of the radial equilibrium conditions. It is shown that many of the flow structures apparently seen in wind and water tunnel visualization studies of delta wing vortices are an artifact of the tracer particle characteristics. In particular, the 'smoke tube' or 'hole' effect often seen in smoke flow visualization in wind tunnels does not (contrary to popular usage) indicate the size of the viscous sub-core and is not a reliable indicator of the vortex structure.

Greenwood, J. S.

"WAKE VORTEX SENSORS"

CS Report 9346, November 1993, Chief Scientist's Division, National Air Traffic Services, London, England.

This report reviews research into wake vortex sensors which has been conducted by the Chief Scientist's Division (CSD) of the National Air Traffic Services (NATS) and other organizations, and sets out options for future work. Further development of a Laser Doppler Velocimeter is recommended.

Greenwood, J. S. and Vaughan, J. M.

"MEASUREMENTS OF AIRCRAFT WAKE VORTICES AT HEATHROW BY LASER DOPPLER VELOCIMETRY"

Air Traffic Control Quarterly, Vol. 6, No. 3, September 1998, pp. 179-203

Measurements of aircraft wake vortices by Laser Doppler Velocimetry can provide unique, full-scale information on vortex generation, evolution, trajectory, and decay in the real atmosphere. During trials at Heathrow nearly 3,000 records of vortices from landing aircraft were made over 25 days spread between November 1994 and September 1995. Examples of some of the initial results are presented, including characteristic vortex signatures and profiles from different aircraft, analysis of vortex strength and trajectory, and an unusual record of a B747 vortex that initially descended but then returned to the

glideslope with virtually undiminished strength 70 seconds after its generation. The way in which this information has been deduced from the measurements is explained fully, and the tradeoffs between the resolution and coverage of measurements are described.

Grinats, E. S. and Stasenko, A. L.

"DEVELOPMENT OF AN ALGORITHM FOR NUMERICAL SIMULATION OF WATER CONDENSATION IN THE JET-VORTEX WAKE OF AN AIRCRAFT AT LOW ATMOSPHERE"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 310-323

The paper presents a physio-mathematical model of the jet-vortex wake behind an aircraft with allowance for heterogeneous condensation of water vapor, inert droplets collisions due to micro-fluctuations of the carrying medium and with modified anisotropic turbulence. In imposing boundary conditions, results of flight tests involving C-130 and OV-10 aircraft were used together with the wind-tunnel data obtained by teams of researchers at NASA and Boeing. Numerical algorithm and tests for a B-747-type heavy aircraft are briefly described in the present work. The materials presented can be used in assessing optical properties of aerosols behind an aircraft with the aim of visualization of its trailing vortices.

Grinats, E. S., Kashevarov, A. V. and Stasenko, A. L.

"NUMERICAL STUDY OF THE JET-VORTEX WAKE BEHIND A HEAVY AIRCRAFT FLYING NEAR THE GROUND"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 137-145

As applied to the problem of aircraft wake visualization over an airfield, gas dynamic and optical characteristics of engine exhaust jets and vortex wakes have been numerically explored with consideration for the heterogeneous condensation of water vapors both being exhausted by the engines and contained in the atmosphere. The influence of the turbulent characteristics of the airflow behind an aircraft was considered on the dissipation rate of the exhaust jets in the near wake. The vicinity of the ground was taken into consideration in studying the mechanics and phase composition of the jet-vortex wake. The spatial distributions were found for concentrations of water vapor and condensate, particle sizes as well as some moments over the particles' mass spectrum, which characterize the dispersive properties of the wake. The calculations were performed for the landing conditions of a B-747 type heavy four-engine aircraft [In Russian].

Grinats, E. S., Kashevarov, A. V. and Stasenko, A. L.

"LIGHT SCATTERING BY CONDENSATE PARTICULATES IN THE VORTEX-JET WAKE BEHIND A CIVIL AIRCRAFT AT LOW HEIGHT"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 113-120

The light scattering by an axisymmetric jet and vortex-jet wake, containing condensate particulates, has been numerically investigated on the basis of Mie's theory of electromagnetic radiation scattering by a single spherical dielectric particulate and the principle of superposition of contributions from individual particulates. Results of the numerical investigations of scattered light characteristics are given for the case of the B-747-type heavy civil aircraft near the ground.

Griswold, II, R. W.

"VORTEX ALLEVIATING WING TIP"

US Patent 4,477,042, October 1984

A wing tip is contoured and shaped to bring about a controlled merger of fluid flows across the upper and lower wing surfaces and alleviation of the resulting vortex when the wing is producing lift or thrust. Control through geometry of the wing tip can be augmented by discharging fluid into the merging flows which weakens the strength of the vortex and results in more rapid dissipation in the wake of an aircraft. Additionally, the origin of the vortex is prevented from migrating inboard of the wing tip which improves overall wing efficiency.

Groenenboom, J. and Levalts, J.

"WING VORTEX VISUALIZATION AND INTERFERENCE PATTERNS"

AIAA Paper No. 1977-0309, Washington, DC, 1977

Two symmetrical airfoils with an elliptical lift distribution were tested in the Iowa State University low-turbulence wind tunnel to determine through visualization the effects of vortex interaction. The first portion of the study was devoted to determining the best method of vortex visualization. It was found that steam injected into the flow forward of the airfoils gave the best delineation. The two wings were tested to determine what effect circulation strength and direction and separation distance had on the vortices at various downstream locations. Test results showed that the vortices interacted by wrapping around one another and merging. The degree of interaction was primarily dependent on separating distance and circulation strength.

Grogger, H. A., Lummer, M. and Lauke, T.

"SIMULATING THE INTERACTION OF A THREE-DIMENSIONAL VORTEX WITH AIRFOILS USING CAA"

AIAA Paper No. 2001-2137, Maastricht, The Netherlands, May 2001

The noise generated by the interaction of localized three-dimensional vorticity with the leading edge of Joukowski-type airfoils is calculated numerically. As governing equations, the linearized Euler-

equations are solved in curvilinear coordinates. For spatial discretization the well-known DRP-scheme is used and for time marching the classical explicit 4th order Runge-Kutta scheme is employed. The mean-flow is pre-calculated analytically. Calculations are performed for three-dimensional vorticity spots striking the leading edge of the airfoil. The influence of the principal fluctuation component on noise generation is assessed by different rotational axes of the vorticity. The investigated airfoils have a thickness of 6, 12 and 18 percent. As limiting case the simulations are also performed for an infinite thin flat plate. Directivity patterns are evaluated and compared.

Groskreutz, A. R. and Dominguez, P. M.

"REQUIRED SURVEILLANCE PERFORMANCE FOR REDUCED MINIMAL-PAIR ARRIVAL SEPARATIONS"

Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015), June 2015, Lisbon, Portugal.

This paper will investigate and propose preliminary Required Surveillance Performance (RSP) requirements associated to a longitudinal arrival separation of 2.0 NM. Just as new regulations requiring navigation are using Required Navigation Performance (RNP) to disassociate the regulation from a particular type of technology and substitute general performance requirements for any current or future navigation technology, an effort is needed to assign RSP requirements in separation minima. RSP requirements have already been set in Europe for 5 NM and 3 NM horizontal separations in en-route flight. Currently referred to as the minimal-pair radar separation, non-wake turbulence longitudinal arrival separations are set by ICAO at 3 NM (or 2.5 NM if conditions permit). Part of the effort in the SESAR 6.8.1 project is to propose a new, non-wake turbulence longitudinal arrival separation of 2.0 NM enabled through Required Surveillance Performance (RSP). The proposed preliminary requirements for a 2 NM minimal-pair arrival separation were achieved using the separation model developed within the RESET project. This model uses the current separation minima and their influencing factors to create a separation assurance budget software tool, identifying the various budget components and influencing factors that contribute to the establishment of separation minima. Although several approaches are possible, this formalization considers the uncertainties in the position, velocity, and aircraft intent as well as all the factors needed for perception, comprehension, and projection of the status of aircraft. This formalization provides the homogeneous means for the technological and procedural assessments in term of contribution to separation minima. To ensure the required TLS, a safety assessment needs to be done to analyze the other factors to present a complete safety case. However, the preliminary results of this study show that a RSP associated with ADS-B seems to be sufficient for a 2 NM minimal-pair arrival separation with current TLS.

Groskreutz, A. R. and Mayer, G. R.

"ANALYSIS OF 2NM SEPARATION FOR MINIMAL PAIR ARRIVALS"

Fifth SESAR Innovation Days, December 2015, Bologna, Italy.

This paper presents preliminary results regarding the conditions in which a 2 NM arrival separation can be implemented taking into consideration the relationship between arrival separation, runway occupancy time, and exit location. The analysis was carried out using expert workshops and Monte Carlo simulations, where the recommendations of the experts were put into simulated conditions. To better simulate various airport conditions, various traffic mix samples were used, varying the percentage of aircraft that could take advantage of the reduced separation between 50 and 80 percent. The proposed re-categorization separation matrix was also used to better simulate future conditions. Average arrival Runway Occupancy Times (AROTs) were given to each aircraft category defined and these values were varied to simulate different exit taxiway layouts. In addition to fast-time simulations, a workshop on the relation between minimal-pair separations and AROT was held. Controllers, pilots and operational experts were in attendance. The objective was to discuss not only the factors that can limit the AROT, but also means to reduce it to take advantage of the reduced separations. It was then shown that these means are sufficient to reduce the AROT so that the 2 NM separations can be used for most aircraft pairs that are not wake turbulence limited. It was also shown that the arrival results show between a 6 and 30 percent capacity improvement depending on the scenarios compared, even without using intelligent sequencing of the aircraft. Further studies are warranted with the inclusion of this type of arrival sequencing.

Grow, T. L.

"THE EFFECT OF WING GEOMETRY AND LOWER SURFACE BOUNDARY LAYER ON THE ROLLED-UP TIP VORTEX"

M.S. Thesis, June 1967, Penn. State Univ., University Park, PA.

A theoretical and an experimental analysis were performed to determine the effect the wing geometry and the boundary layer on the lower surface of the wing have on the size and strength of the rolled-up tip vortex. The theoretical analysis was limited by the inherent three-dimensional properties of the flow. An extensive experimental investigation provided results which adequately described the vortex strength and geometry for the many wing configurations which were tested. From these results the size and strength of the rolled-up tip vortex can be predicted for any wing with similar geometry and Reynolds number.

Grow, T. L.

"EFFECT OF A WING ON ITS TIP VORTEX"

Journal of Aircraft, Vol. 5, No. 2, March-April 1968, pp. 37-41

A theoretical and an experimental analysis was performed to determine the effect that the wing geometry and the boundary layer on the lower surface of the wing have on the trailing rolled-up tip vortex. Model test results are presented for the vortex structure downstream of wings of varying aspect ratio and taper ratio. The geometry and strength of the rolled-up tip vortices were measured over a range of lift coefficients. In general, it was found that the strength of the vortex is less than one

would predict based on the midspan circulation about the wing. Conclusions are given regarding the size and strength of a vortex as they relate to the wing aspect ratio, taper ratio, and lift coefficient.

Gryazin, V. E.

"ALLEVIATION OF THE WAKE VORTEX EFFECT ON THE TRAILING AIRCRAFT THROUGH AUTOMATION OF THE FLIGHT-DIRECTOR CONTROL AT LANDING APPROACH"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 247-254

The author considers feasible means to alleviate hazardous effects of the aircraft wake on a trailing aircraft after it has been detected by the onboard automatic wake detection system [Gryazin and Poyedinok 1997]. Both lateral maneuver, to avoid the vortex core, and automatic additional deflection of the control surfaces are shown to solve the problem. Piloted simulation of the aircraft landing approach has proven sufficient effectiveness of the proposed means.

Gryazin, V. E.

"ANALYSIS OF THE WAKE VORTEX DETECTION SYSTEM NOISE IMMUNITY UNDER CONDITIONS OF TURBULENT ATMOSPHERIC BOUNDARY LAYER"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 255-262

The paper dwells upon modeling algorithms for the surface air turbulence presented as a 3D velocity field, thus enabling modeling of the wind gusts distribution over the aircraft airframe. These algorithms are then employed to assess noise immunity of the vortex detection system in the conditions of atmosphere turbulence.

Gryazin, V. E.

"RESEARCH ON AIRCRAFT FLIGHT SAFETY IN WAKE TURBULENCE CONDITIONS THROUGH PILOT-IN-THE-LOOP SIMULATION"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 225-228

A piloted simulation has been carried out of the flight dynamics of a transport category aircraft ($G=25$ t - weight, $S=82$ square meters - wing area, $l=30$ m - wing span) during landing approach in wake turbulence conditions. It was shown that according to opinions of test pilots who flew the simulation aircraft wakes pose a significant hazard to encountering aircraft ($PR > 6$, i.e. the third level of pilot's perceive handling qualities rating) when the wake-induced rolling moments exceed 50% of the maximum rolling moment at full aileron deflection. In such conditions, roll angles can exceed the maximum allowable value (10 degrees). If the pilot is provided with information on his aircraft

approaching a vortex wake, he will be able to counteract the rolling moment induced by the wake, such a moment sometimes reaching the aircraft maximum roll control authority.

Gryazin, V. E. and Poyedinok, V. M.

"ALGORITHMS OF VORTEX WAKE DETECTION AND FLIGHT-DIRECTOR CONTROL FOR EXECUTING WAKE-AVOIDANCE MANEUVERS"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 121-131.

The algorithms for the on-board vortex-wake detection system has been synthesized. The existing airborne equipment is shown to allow timely detecting of wake vortices and determining their position relative to the aircraft. Algorithms have been proposed for the flight-director control system intended for executing a side vortex-wake-avoidance maneuver. Being employed the system can help to reduce now adopted safe-separation distances in landing approach.

Gu, Y., Napolitano, M., Gross, J., Chao, H., Zheng, C. Z. and Rhudy, M.

"COOPERATIVE GUST SENSING AND SUPPRESSION FOR AIRCRAFT FORMATION FLIGHT, PHASE II"

Leading Edge Aeronautics Research for NASA (LEARN) research report, December 2016, West Virginia University, Morgantown, WV.

Autonomous formation flight is an enabling technology for many future concepts of operations involving both manned and unmanned aircraft. Its potential benefits include energy saving and improved aircraft coordination within a high-density airspace. However, with the following aircraft constantly flying in the leader's wake, several technical challenges need to be overcome before commercial aircraft and Unmanned Aerial Vehicles (UAVs) can routinely and safely fly in formation. Many challenges are related to the modeling, prediction, and real-time sensing of the dynamic airflow field, which includes both ambient and wake-induced wind gust disturbances. The objective of this overall research effort was to develop and experimentally validate a cooperative strategy for gust sensing and suppression within a close formation flight setting. During the Phase I effort, a real-time wind estimation algorithm was developed. Additionally, the concept of cooperative wind sensing was validated in simulation studies. Furthermore, autonomous close formation flights were achieved using two sub-scale research aircraft at a 5x wingspan distance. The effects of the wake vortices were successfully recorded by sensors onboard the follower aircraft. During the Phase II effort, wake identification from UAV formation flight data was performed. An integrated aerodynamics and flight dynamic simulator for UAS wake encounters was developed using the vortex lattice method. Four different wind speed estimation algorithms were developed and compared using simulated and flight data. The research test beds were upgraded with new sensors, propulsion systems, communication devices, and newly designed avionics. Over 45 flight testing experiments were performed for supporting system integration tasks and for collecting research data. A relative navigation algorithm fusing measurements provided by a carrier phase differential GPS receiver, inertial sensors, and ranging

radios was developed to improve the robustness of the navigation solution. A novel computer vision-based airflow angle estimation method was also developed and validated with flight data. Each of these technical developments are presented in this report.

Guerin, D.

"CONSIDERATION OF WAKE TURBULENCE DURING THE INTEGRATION OF REMOTELY PILOTED AIRCRAFT INTO THE AIR TRAFFIC MANAGEMENT SYSTEM"

Proceedings of the 2015 International Conference on Unmanned Aircraft Systems (ICUAS), June 2015, Denver, CO, pp. 926-935.

The last decade has witnessed both the growth in Remotely Piloted Aircraft (RPA) numbers and the introduction of the Airbus A380, the largest passenger aircraft to enter commercial service. Both introduce extremes at either end of the spectrum for weight and wingspan: into an Air Traffic Management (ATM) where wake vortex separation minima have been unchanged for three decades. However, airport congestion may compel a rethink, and the mandated separation distances in place for wake turbulence are under scrutiny. Remotely Piloted Aircraft Systems (RPAS) will inject yet another permutation into deliberation for separation standards and wake turbulence considerations. However, aside from complicating the space, RPA offer a means to reduce the mandated gaps, and subsequently alleviate capacity issues. This paper examines wake turbulence and its effects and proposes trials to reinforce reductions or expansions of present and future separation minima.

Guerreiro, N. M. and Neitzke, K. W.

"SIMULATED WAKE CHARACTERISTICS DATA FOR CLOSELY SPACED PARALLEL RUNWAY OPERATIONS ANALYSIS"

AIAA Paper 2012-5642, September 2012, Indianapolis, Indiana.

A simulation experiment was performed to generate and compile wake characteristics data relevant to the evaluation and feasibility analysis of closely spaced parallel runway (CSPR) operational concepts. While the experiment in this work is not tailored to any particular operational concept, the generated data applies to the broader class of CSPR concepts, where a trailing aircraft on a CSPR approach is required to stay ahead of the wake vortices generated by a lead aircraft on an adjacent CSPR. Data for wake age, circulation strength, and wake altitude change, at various lateral offset distances from the wake-generating lead aircraft approach path were compiled for a set of nine aircraft spanning the full range of FAA and ICAO wake classifications. A total of 54 scenarios were simulated to generate data related to key parameters that determine wake behavior. Of particular interest are wake age characteristics that can be used to evaluate both time- and distance-based in-trail separation concepts for all aircraft wake-class combinations. A simple first-order difference model was developed to enable the computation of wake parameter estimates for aircraft models having weight, wing span and speed characteristics similar to those of the nine aircraft modeled in this work.

Guerreiro, N. M., Neitzke, K. W., Johnson, S. C., Stough III, H. P., McKissick, B. T. and Syed, H. I.

"CHARACTERIZING A WAKE-FREE SAFE ZONE FOR THE SIMPLIFIED AIRCRAFT-BASED PAIRED APPROACH CONCEPT"

AIAA Paper No. 2010-7681, Toronto, Canada, August 2010.

The FAA has proposed a concept of operations geared towards achieving increased arrival throughput at U.S. Airports, known as the Simplified Aircraft-based Paired Approach (SAPA) concept. In this study, a preliminary characterization of a wake-free safe zone (WSZ) for the SAPA concept has been performed. The experiment employed Monte-Carlo simulations of varying approach profiles by aircraft pairs to closely-spaced parallel runways. Three different runway lateral spacings were investigated (750 ft, 1000 ft and 1400 ft), along with no stagger and 1500 ft stagger between runway thresholds. The paired aircraft were flown in a leader/trailer configuration with potential wake encounters detected using a wake detection surface translating with the trailing aircraft. The WSZ is characterized in terms of the smallest observed initial in-trail distance leading to a wake encounter anywhere along the approach path of the aircraft. The results suggest that the WSZ can be characterized in terms of two primary altitude regions, in ground-effect (IGE) and out of ground-effect (OGE), with the IGE region being the limiting case with a significantly smaller WSZ. Runway stagger was observed to only modestly reduce the WSZ size, predominantly in the OGE region.

Guevremont, G., Habashi, W. G., Kotiuga, P. L. and Hafez, M. M.

"FINITE ELEMENT SOLUTION OF THE 3D COMPRESSIBLE NAVIER-STOKES EQUATIONS BY A VELOCITY-VORTICITY METHOD"

Journal of Computational Physics, Vol. 107, 1993, pp. 176-187

This paper presents an alternative formulation to the primitive variable form of the Navier-Stokes equations. The approach is based on the use of the velocity and vorticity variables as a logical extension of the stream function-vorticity method which is quite effective for two-dimensional flows. Second-order equations are obtained for the variables and discretization is through a weak-Galerkin finite element method, followed by Newton linearization. The velocity and vorticity components are solved simultaneously by a direct solver. The scheme is demonstrated for two-dimensional and three-dimensional incompressible and subsonic internal enclosed flow problems.

Guha, T. K.

"ACTIVE CONTROL OF WINGTIP VORTICES USING PIEZOELECTRIC ACTUATED WINGLETS"

PhD Thesis, Summer 2017, Florida State University, Tallahassee, FL.

Wingtip vortices develop at the tips of aircraft wings due to a pressure imbalance during the process of generating lift. These vortices significantly increase the total aerodynamic drag of an aircraft at high-lift flight conditions such as during take-off and landing. The long trailing vortices contain strong circulation and may induce rolling moments and lift losses on a trailing aircraft, making them a major

cause for wake turbulence. A mandatory spacing between aircraft is administered by civil aviation agencies to reduce the probability of hazardous wake encounters. These measures, while necessary, restrict the capacity of major airports and lead to higher wait times between take-off and landing of two aircraft. This poses a major challenge in the face of continuously increasing air traffic volume. Wingtip vortices are also known as a potent source of aerodynamic vibrations and noise. These negative effects have made the study of wingtip vortex attenuation a critical area of research. The problem of induced drag has been addressed with the development of wingtip device, like winglets. Tip devices diffuse the vortex at its very onset leading to lower induced drag. The problem of wake turbulence has been addressed in studies on vortex interactions and co-operative instabilities. These instabilities accelerate the process of vortex breakdown, leading to a lower lifetime in the wake. A few studies have tried to develop active mechanisms that can artificially excite these instabilities. The aim of the present study is to develop a device that can be used for both reducing induced drag and exciting wake instabilities. To accomplish this objective, an active winglet actuator has been developed with the help of piezoelectric Macro-Fiber Composite (MFC). The winglet is capable of oscillating about the main wing-section at desired frequency and amplitude. A passive winglet is a well-established drag reducing device. An oscillating winglet can introduce perturbations that can potentially lead to instabilities and accelerate the process of vortex breakdown. A half-body model of a generic aircraft configuration was fabricated to characterize and evaluate the performance of actuated winglets. Two winglet models having mean dihedral orientations of 0 degree and 75-degree were studied. The freestream velocity for these experiments was 20 m/s. The angle of incidence of the wing-section was varied between 0 degree and 8-degree. The Reynolds number based on the mid-chord length of the wing-section is 140000. The first part of the study consisted of a detailed structural characterization of the winglets at various input excitation and pressure loading conditions. The second part consisted of low-speed wind tunnel tests to investigate the effects of actuation on the development of wingtip vortices at different angles of incidence. Measurements included static surface pressure distributions and Stereoscopic (ensemble and phase-locked) Particle Image Velocimetry (SPIV) at various downstream planes. Modal analysis of the fluctuations existing in the baseline vortex and those introduced by actuation is conducted with the help of Proper Orthogonal Decomposition (POD) technique. The winglet oscillations show bi-modal behavior for both structural and actuation modes of resonance. The oscillatory amplitude at these actuation modes increases linearly with the magnitude of excitation. During wind tunnel tests, fluid structure interactions lead to structural vibrations of the wing. The effect of these vibrations on the winglet oscillations decreases with the increase in the strength of actuation. At high input excitation, the actuated winglet can generate controlled oscillations suitable for perturbing the vortex. The vortex associated with a winglet is stretched along its axis with multiple vorticity peaks. The center of the vortex core is seen at the root of the winglet while the highest vorticity levels are observed at the tip.

Guha, T. K. and Kumar, R.

"CHARACTERISTICS OF A WINGTIP VORTEX FROM AN OSCILLATING WINGLET"

Experiments in Fluids, Vol. 58, 2017, pp. 8-1 to 8-18.

Initial perturbations in the wingtip vortices can potentially lead to instabilities that significantly reduce their lifetime in the wake of an aircraft. An active winglet capable of oscillating about its point of attachment to the main wing-section is developed using piezoelectric macro fiber composite, to actively perturb the vortex at its onset. Resonance characteristics of the actuated winglet oscillations are evaluated at different excitation levels and aerodynamic loading. Mean near-field characteristics of the vortex, developing from a stationary and an oscillating winglet, are investigated with the help of stereoscopic particle image velocimetry. Results show that the amplitude of winglet oscillations increases linearly with input excitation, to a highest attainable value of nearly four times the airfoil thickness at the winglet tip. The vortex developing from a winglet is stretched along its axis, having an elliptical core with non-uniform vorticity distribution. Actuation leads to spatial oscillations of the vortex core together with a reduction in the mean peak vorticity levels. The amplitude of the actuated core oscillations remains constant in the investigated region of the wake.

Guha, T. K. and Kumar, R.

"ACTIVE CONTROL OF WINGTIP VORTICES USING PIEZOELECTRIC ACTUATED WINGLETS"

AIAA Paper 2016-0323, January 2016, San Diego, CA.

Wingtip vortices are caused by the pressure difference between the upper and lower surface of a wing equalizing at the tip. In the present study, piezoelectric Marco Fiber Composite (MFC) actuated winglets have been designed and developed to control the initiation and development of wingtip vortices. A half model of a generic aircraft configuration was fabricated to characterize and evaluate the performance of actuated winglets. Actuated winglets are capable of oscillating about their mean dihedral position with varying amplitudes and frequencies. Measurements include surface pressure distributions, planar and stereoscopic (ensemble averaged and phase locked) Particle Image Velocimetry at various downstream locations to study the effect of actuation on wingtip vortex development and diffusion. Vortex developing around a winglet has a core that is stretched along the axis of the winglet, and the vorticity distribution show two unequal peaks. This vortex stretching indicates that the net circulation is distributed over a large region leading to lower levels of peak vorticity, which translates into lower induced drag and faster decay. With MFC actuation, there appears to be further stretching in the tip vortex leading to lower peak vorticity levels.

Guidry, M., Whitley, S. and Markowich, B.

"BOEING 767 PROXIMITY EVALUATION WITH F/A-18C AND S-3B AIRCRAFT"

NAWCADPAX/RTR-2001/17, March 2001, Naval Air Warfare Center Aircraft Division, Patuxent River, MD

The Boeing company participated in the Future Strategic Tanker Aircraft program which was intended to provide aerial refueling and aerial transport capability. This study was to determine if an area of acceptable wake turbulence existed in the proximity of a 767 in order to perform the aerial refueling mission. This was accomplished by evaluating the 767 aerodynamic and wake turbulence effects on two receiver aircraft (F/A-18C and S-3B) at locations behind the 767, which approximated potential

aerial refueling engagement areas. A Lear 35 cinematography aircraft was used to document test results.

Guignery, F., Vancassel, X., Montreuil, E. and Thual, O.

"NUMERICAL SIMULATION OF CONTRAIL FORMATION USING A SIMPLIFIED WING-INJECTOR CONFIGURATION"

AIAA Paper No. 2009-3868, San Antonio, Texas, June 2009.

Contrail formation is a complex topic, since several physical processes are involved, covering a large range of space and time scales, from the engine exit to the atmospheric global scale. In the near field of the aircraft, contrail formation is mainly dominated by microphysics and mixing processes between the propelling jets and the external flow and more precisely during the jet-vortex interaction. In this paper, we present a new approach to focus on the influence of the wing/nacelle configuration on contrail onset. The originality of this work is to provide a preliminary study to consider a complex aircraft geometry in further jet vortex numerical simulations using the ONERA multi-physics code CEDRE.

Guj, G. and Stella, F.

"A VORTICITY-VELOCITY METHOD FOR THE NUMERICAL SOLUTION OF 3D INCOMPRESSIBLE FLOWS"

Journal of Computational Physics, Vol. 106, 1993, pp. 286-298

A new method for the numerical solution of the 3D Navier-Stokes equations written in terms of vorticity-velocity is presented. The advantages of this formulation with respect to primitive variables and vorticity-vector-potential ones are discussed in view of physical as well as engineering applications. A suitable form of the continuum equations, the most appropriate discretization scheme, and variable location in order to guarantee the solenoidality of the velocity and vorticity fields are introduced and justified. A 3D lid driven cavity problem for $400 \leq Re \leq 3200$ is chosen as a test case for comparison and validation purposes. A parallel implementation of the method has been performed on a shared memory architecture mainframe. Speedup results and efficiency considerations are given and discussed.

Gunasekaran, M. and Mukherjee, R.

"A NUMERICAL STUDY OF THE AERODYNAMICS OF CESSNA 172 AIRCRAFTS IN ECHELON FORMATION"

AIAA Paper 2014-1107, January 2014, National Harbor, MD.

A vortex-lattice numerical scheme that uses a novel decambering technique to predict post-stall aerodynamic characteristics is used to study the aerodynamics of tandem Cessna 172 aircrafts flying in echelon formation. Results like $C_{L-\alpha}$ from the current method are compared with experiment. Additional results like section C_{L} distributions over wing spans, $C_{M-\alpha}$ and $C_{LW-\alpha}$ (i.e. C_{L} of the leading aircraft for different angles of attack of the trailing

aircraft) and analysis for y -offset, which are available only from the current numerical method are reported that supplement the experimental results. Detailed post-stall numerical analysis and the effect of chord-wise, span-wise and vertical offsets on the aerodynamics of the formation are also reported.

Gunasekaran, S. and Altman, A.

"IS THERE A RELATIONSHIP BETWEEN THE TURBULENCE CHARACTER OF THE WINGTIP VORTEX AND THE WING FREE SHEAR LAYER?"

AIAA Paper 2016-1068, January 2016, San Diego, CA.

PIV experiments were conducted in the wake of an aspect ratio 4 flat plate at the University of Dayton's Low Speed Wind Tunnel (UD-LSWT) to determine the existence of any relationship between the wingtip vortex and the wing's free shear layer. Several modifications were made to the wing boundary layer to investigate sensitivity to a range of boundary layer conditions. To explore this relationship, the mid semi-span free shear layer and the wingtip vortex were interrogated at various chord lengths distance downstream and across an angle of attack range of 1 to 4 degrees in the vicinity of the maximum (L/D) lift condition. The development of the wingtip vortex was examined with three primary fields of view oriented along the three axes (Streamwise, Cross-stream and Spanwise). Then a boundary layer trip was introduced on the upper surface of the flat plate to change the character of the turbulence in the boundary layer. The resulting changes in the turbulence character of the wingtip vortex and free shear layer were interrogated for evidence of an interaction between the free shear layer and the wingtip vortex. A significant relationship between the shear layer and the wingtip vortex was ultimately found and will be elaborated in detail.

Gunasekaran, S. and Altman, A.

"REFINED INSIGHT INTO THE WINGTIP VORTEX-FREE SHEAR LAYER INTERACTION"

AIAA Paper 2017-1705, January 2017, Grapevine, TX.

Interaction between the free shear layer (FSL), the wingtip vortex and aerodynamic efficiency was observed. These results were quantitatively evaluated through Particle Image Velocimetry (PIV) of the wingtip vortex and the free shear layer (FSL) obtained in the Low Speed Wind Tunnel at the University of Dayton (UD-LSWT). The experiments were conducted in the wake of an AR 4 flat plate with and without a boundary layer trip (BLT). The effect of the BLT on both the FSL and the wingtip vortex was previously documented. In the present work, the analysis was extended to explore the role the FSL interaction plays in the wingtip vortex evolution. Additionally, a correlation between this FSL-wingtip vortex interaction and the aerodynamic efficiency of the wing was sought. Streamwise, cross-stream and spanwise plane-oriented PIV of the wingtip vortex shows evidence of the FSL interaction with the wingtip vortex at lower angles of attack. Due to the FSL interaction with the wingtip vortex, vortex profiles predicted using Batchelor's and Brown's models deviate from the experimental data. The composite of the experimentally determined velocity profiles from different planes implied an

exchange of momentum between the FSL and the wingtip vortex in the vicinity of the maximum (L/D) lift condition. At an angle of attack less than that of maximum (L/D), the additional loss of momentum due to the BLT is seen in the wing wake FSL. At an angle of attack greater than that corresponding to the maximum (L/D), the additional loss of momentum due to the BLT is instead seen in the wingtip vortex.

Gunasekaran, S. and Altman, A.

"IDENTIFICATION OF AIRCRAFT BY THEIR UNIQUE TURBULENT WAKE SIGNATURE: PROGRESS WITH EXPERIMENTAL VALIDATION"

AIAA Paper 2013-1120, January 2013, Grapevine, TX.

The theoretical foundation for the identification of aircraft by their unique turbulent wake signature is experimentally validated. A brief review of this theoretical foundation will be discussed wherein the drag coefficient can be used to estimate either a Reynolds Stress distribution or [indirectly] a model of the profile of the fluctuating streamwise velocity component of the turbulent wake. Previously, the Reynolds stress distributions downstream of a circular cylinder, moderate aspect ratio wing and small remote control twin motor aircraft were determined using Particle Image Velocimetry (PIV) in the University of Dayton low speed wind tunnel. Those results were compared to the predicted Reynolds Stress distributions calculated from the drag coefficient obtained through direct force measurement. The cylindrical results validated the implementation of the method. The wing and aircraft results, however, were inconclusive since the wind tunnel test section was not long enough to guarantee that a self-preserved state had been achieved in the wake. For this paper, a wall-to-wall SD7003 wing profile and an aspect ratio 4 flat plate wing are tested in a much longer test section at the Air Force Research Labs Horizontal Free Surface Water Tunnel. The wakes are interrogated in streamwise planes using PIV at distances downstream ranging from 6 to 20 chord lengths. These results are then compared to the predicted Reynolds stress distributions determined from drag data available in the literature and from direct drag force measurement respectively for the two wing models. When using empirical tuning as a surrogate for a more rigorous determination of turbulence eddy viscosity the predicted Reynolds stress distributions compare extremely well across a wide range of angles of attack and chordwise PIV planes of interrogation (from mid semi-span to the wingtip). Asymmetry is present in the Reynolds Stress distribution and the theoretical model can be adjusted to account for it. The presence of the wingtip vortex does not prevent successful application of the model in the finite wing test.

Gundling, C., Roget, B. and Sitaraman, J.

"PREDICTION OF WIND TURBINE PERFORMANCE AND WAKE LOSSES USING ANALYSIS METHODS OF INCREMENTAL COMPLEXITY"

AIAA Paper 2011-0458, January 2011, Orlando, FL.

This paper compares several methods for predicting wind turbine performance, as well as predicting wake interference in a wind farm. The analysis tools range from the full CFD calculations at the high

complexity end to a traditional Blade Element Momentum based approach at the low complexity end. We perform full CFD calculations using the HELIOS (Helicopter Overset Simulations) code. HELIOS provides a novel meshing approach to CFD with body conforming unstructured grids near the solid walls and solution adaptive Cartesian grids away from the walls. This approach is particularly suited for vortex wake dominated flows such as those observed in wind turbine flow fields, where effective wake capturing depends largely on numerical dissipation. The different analytical methods are first applied to a model of the horizontal axis two-bladed rotor of the NREL Phase VI Unsteady Aerodynamic Experiment and then to a model of the 3-bladed turbines of the experimental Sexblerum wind farm. We further compare wake deficits behind an isolated turbine using the subset of methodologies that allow for probing of flow fields. Finally, we apply two of the chosen methodologies for studying performance losses caused by wake interference. In particular, we analyze the performance losses and nature of wind deficit when two turbines are operating, one behind the other, in pure axial flow condition.

Gundling, C., Roget, B., Sitaraman, J. and Rai, R.

"COMPARISON OF WIND TURBINE WAKES IN STEADY AND TURBULENT INFLOW"

AIAA Paper No. 2012-0899, January 2012, Nashville, TN.

This paper presents simulation results of wake effects in a wind farm, under both steady and turbulent inflow conditions. Depending on a wind farm's design, wake interference can cause large power losses and increased turbulence levels. The extent of these wake interference effects depends strongly on the atmospheric inflow conditions. The objective of the present study is to employ several modeling methods to reach an improved understanding of wake effects and to use this information to better optimize a farm's layout. The methods used in order of low to high complexity are: a blade element model with free-vortex wake approach for inflow (UWake), an actuator disk-based Reynolds-averaged Navier-Stokes (RANS) Computational Fluid Dynamics (CFD) method (DiskFlow) and a full blade RANS CFD code (HELIOS) that utilizes adaptive mesh refinement (AMR). The methods are collectively employed to model wind turbines at the Sexblerum wind farm, which allows for comparisons to experimental data and also for cross comparisons between the models. Single turbine wake deficits are modeled using both steady and turbulent inflow. Inflow turbulence is introduced using data from a precursor large eddy simulation (LES) of a neutral atmospheric boundary layer (ABL). A two-turbine exact row case is also modeled to investigate the dependence of the power deficit at the downstream turbine on inflow conditions. The differences in the diffusion of the wake with and without turbulent inflow are presented, and the limitations of each method are discussed.

Gunes, T. and Erdol, N.

"HMM BASED SPECTRAL FREQUENCY LINE TRACKING: IMPROVEMENTS AND NEW RESULTS"

IEEE Proceedings, Vol. 2, May 2006, pp. II-673-II-676

This paper considers the application of Hidden Markov Models to the problem of tracking frequency lines in spectrograms of strongly non-stationary signals such as encountered in aero-acoustics and sonar where tracking difficulties arise from low SNR and large variances associated with spectral estimates. In the proposed method, we introduce a novel method to determine the observation (measurement) likelihoods by interpolation between local maxima. We also show that use of low variance AutoRegressiveMultiTaper (ARMT) spectral estimates results in improved tracking. The frequency line is tracked using the Forward-Backward algorithm.

Gunzburger, M. and Peterson, J.

"VORTICES IN SUPERCONDUCTORS"

In *Vortex Dominated Flows*, edited by D. Blackmore, E. Krause and C. Tung, 2005, World Scientific, New Jersey, Chapter 4, pp. 67-85.

Fluid vortices have fascinated mankind from time immemorial and have been the subject of interest since the dawn of scientific inquiry. Superconducting vortices are of much more recent vintage, but are an equally fascinating phenomenon. Vortices in superconductors are tubes of magnetic flux, or equivalently, cylindrical current loops, that penetrate a material sample. Knowledge about the structure and dynamics of superconducting vortices are of importance both to the understanding of the basic physics of superconductors and to the design of devices. Vortices in superconductors can be modeled on several scales, from the microscopic to the macroscopic. Here, we concentrate on providing a brief review of mesoscopic-scale models for superconductivity, namely the Ginzburg-Landau equations and variants thereof. At this scale, superconducting vortices are analogous to viscous fluid models that consist of a collection of discrete vortices. The basic model holds for homogeneous, isotropic superconductors; the variants can account for inhomogeneities and anisotropies due to impurities, thickness variations, and thermal fluctuations. These all affect the vortex state, as do changes in the applied magnetic field and current strengths and directions. We use computational simulations to illustrate these effects.

Gunzburger, M. D.

"LONG TIME BEHAVIOIR OF A DECAYING VORTEX"

ZAMM, Vol. 53, 1973, pp. 751-760

The motion and decay of a vortex submerged in a two-dimensional inviscid stream is considered with view of seeking solutions valid for all time. A multiple time scale perturbation scheme is used to obtain solutions. The important effects of viscosity near the center of the vortex are included by a systematic procedure. To illustrate the theory solutions are then presented for the motion of a vortex subject to a sudden uniform gust and for the motion of a vortex in the presence of a wall.

Guo, S., De Los Monteros, J. E. and Lin, Y.

"GUST ALLEVIATION OF A LARGE AIRCRAFT WITH A PASSIVE TWIST WINGTIP"

Aerospace, Vol. 2, 2015, pp. 135-154.

This paper presents an investigation into the gust response and wing structure load alleviation of a 200-seater aircraft by employing a passive twist wingtip (PTWT). The research was divided into three stages. The first stage was the design and analysis of the baseline aircraft, including aerodynamic analysis, structural design using the finite element (FE) method and flutter analysis to meet the design requirements. Dynamic response analysis of the aircraft to discrete (one-cosine) gust was also performed in a range of gust radiances specified in the airworthiness standards. In the second stage, a PTWT of a length of 1.13 m was designed with the key parameters determined based on design constraints and, in particular, the aeroelastic stability and gust response. Subsequent gust response analysis was performed to evaluate the effectiveness of the PTWT for gust alleviation. The results show that the PTWT produced a significant reduction of gust-induced wingtip deflection by 21 percent and the bending moment at the wing root by 14 percent in the most critical flight case. In the third stage, effort was made to study the interaction and influence of the PTWT on the symmetric and unsymmetrical maneuvering of the aircraft when ailerons were in operation. The results show that the PTWT influence with a reduction of the aircraft normal velocity and heave motion by 1.7 percent and 3 percent, respectively, is negligible. However, the PTWT influence on the aircraft roll moment with a 20.5 percent reduction is significant. A locking system is therefore required in such a maneuvering condition. The investigation has shown that the PTWT is an effective means for gust alleviation and, therefore, has potential for large aircraft application.

Guo, Y.

"ON NOISE REDUCTION BY FLAP SIDE EDGE FENCES"

Journal of Sound and Vibration, Vol. 277, Issues 1-2, October 1994, pp. 369-390

This paper discusses the effects of fences on side edge cross flows. Experimental data are reviewed to show that fences can modify the cross flow in the side edge region of aircraft flaps in such a way that noise reduction can be achieved. Near field pressure data reveal that fences reduce the characteristic frequency of the flow fluctuations. This leads us to postulate that the fences make the far field noise spectra shift downward in frequency. Because airframe noise spectra typically have a negative slope in the most important mid to high frequency domain, this downward shift in frequency leads to an equivalent reduction of noise levels, when measured by conventional metric such as the effective perceived noise level in aircraft certification. To explain the decrease of the characteristic frequency of the flow fluctuations due to the fences, an analytical model is developed, based on vortex dynamics. The predictions from the model are shown to be in very good agreement with measured data, both for the dominant frequency in the baseline case without the fences and for the trends of the decreasing frequency with increasing fence height.

Guo, Y. P., Joshi, M. C., Bent, P. H. and Yamamoto, K. J.

"SURFACE PRESSURE FLUCTUATIONS ON AIRCRAFT FLAPS AND THEIR CORRELATION WITH FAR-FIELD NOISE"

Journal of Fluid Mechanics, Vol. 415, 2000, pp. 175-202.

This paper discusses unsteady surface pressures on aircraft flaps and their correlation with far-field noise. Analyses are made of data from a 4.7 percent DC-10 aircraft model test, conducted in the 40 x 80 feet wind tunnel at NASA Ames Research Center. Results for various slat/wing/flap configurations and various flow conditions are discussed in detail to reveal major trends in surface pressure fluctuations. Spectral analysis, including cross-correlation/coherence, both among unsteady surface pressures and between far-field noise and near-field fluctuations, is used to reveal the most coherent motions in the near field and identify potential sources of noise related to flap flows. Dependencies of surface pressure fluctuations on mean flow Mach numbers, flap settings and slat angles are discussed. Dominant flow features in flap side edge regions, such as the formation of double-vortex structures, are shown to manifest themselves in the unsteady surface pressures as a series of spectral humps. The spectral humps are shown to correlate well with the radiated noise, indicating the existence of major noise sources in flap side edge regions. Strouhal number scaling is used to collapse the data with satisfactory results. The effects of flap side edge fences on surface pressures are also discussed. It is shown that the application of fences effectively increases the thickness of the flaps so that the double-vortex structures have more time to evolve. As a result, the characteristic timescale of the unsteady sources increases, which in turn leads to a decrease in the dominant frequency of the source process. Based on this, an explanation is proposed for the noise reduction mechanism of flap side edge fences.

Guo, Y., Hallstrom, C. and Spirn, D.

"DYNAMICS NEAR AN UNSTABLE KIRCHHOFF ELLIPSE"

Comm. in Math. Phys., Vol. 245, 2004, pp. 297-354

We describe the dynamics of the Kirchhoff ellipse by formulating a nonlinear equation for the boundary of a perturbed vortex patch in elliptical coordinates. We demonstrate that in the regime for which the linearized equation of motion is unstable, the nonlinear dynamics of a rather general initial perturbation of the Kirchhoff ellipse are determined by the fastest growing mode for the corresponding linearized equation, on a time scale when the nonlinear instability occurs. In particular, we resolve a question suggested by Love's results and prove that such elliptical patches are indeed unstable in the full nonlinear sense.

Gupta, B. P. and Loewy, R. G.

"THEORETICAL ANALYSIS OF THE AERODYNAMIC STABILITY OF MULTIPLE, INTERDIGITATED HELICAL VORTICES"

AIAA Journal, Vol. 12, No. 10, October 1974, pp. 1381-1387.

A small perturbation stability analysis of a doubly infinite array of interdigitated, right circular helical vortices has been formulated. This array corresponds to the vortices trailed from the tips of the blades of a helicopter rotor or propeller in static thrust or axial flight condition and at great distance from the plane of rotation of the blades. A continuum of instability modes has been found associated with all values of wave numbers; only modes with wave numbers 0 and 1 are so much as neutrally stable, and for the case of a single helix. The most unstable modes involve the most axial motion of adjacent vortex segments relative to each other. Maximum divergence rates increase as the helix pitch decreases, increase as the number of helices increase and decrease as the number of cycles of deformations in one turn of the helix (i.e., wave number) increases. The helix filament core diameter can have substantial effect on the stability of a single helix, but not for multiple arrays. The larger the core diameter, the more sensitive the analysis is to how the singularities in the self-induction integrals are eliminated. Increasing core diameters reduces the maximum divergence rates in all cases.

Gupta, M.

"INVESTIGATION OF ACTIVE CONTROL OF AIRCRAFT WING TIP VORTICES AND WAKE TURBULENCE"

MS Thesis, December 2011, Auburn University, Auburn, Alabama.

The present work was focused on study and application of active flow control methods to alleviate the wake turbulence problem in commercial aircraft. Sinusoidal perturbations were introduced into the tip vortex generated off one of the wings in a two-wing system. Various forcing frequencies and oscillation amplitudes were investigated in a towing tank facility. Measurement techniques included invasive and non-invasive methodologies such as flow visualization, hot film anemometry and particle image velocimetry (PIV). Tilting of the plane of the vortices under forcing conditions was observed. The initiation of long-wave Crow instability was observed. This was also confirmed by flow visualization results. For 20Hz forcing frequency, elliptical deformation of the core for both the vortices was observed. This was an indication of short-wave Elliptic instability. When perturbed at a particular frequency and amplitude, the overall system showed earlier onset of instabilities.

Gupta, S. and Leishman, J. G.

"ACCURACY OF THE INDUCED VELOCITY FROM HELICOIDAL VORTICES USING STRAIGHT-LINE SEGMENTATION"

AIAA Journal, Vol. 43, No. 1, January 2005, pp. 29-40

The accuracy of a straight-line segmentation approximation to a series of helicoidal vortices is considered. The problem is examined for different values of the helical pitch, the number of wake turns, and the wake skew angle. Results documenting both the accuracy and the relative errors of the discretized helical vortex and a vortex ring are compared. It is found that with sufficiently small segments, straight-line segmentation of both the vortex ring and of the helical vortex give at least a second-order accurate reconstruction of the induced velocity field. It is shown that the vortex ring can be viewed as a special case of a helical vortex as its pitch tends to zero. Based on the magnitude of the

errors found for the two cases, a vortex ring is shown to be a more stringent test case than a helical vortex when the straight-line segmentation approach is used. The accuracy of the induced velocity field when a skewed helix is represented by straight-line segmentation is shown to be second-order accurate for various combinations of helical pitch and wake skew angle. A comparison with the unskewed helical vortex reveals that the errors in the induced velocity field are almost the same in the two cases.

Gupta, V. P.

"VORTEX-RELATED ACCIDENTS OVER THE TEN YEAR PERIOD 1964-1973"

FAA-EM-75-6, April 1975, MITRE Corp., McLean, VA

Out of the approximately 45,000 aviation accidents that occurred over the ten-year period 1964-73, in the conterminous United States, wake vortices have been cited as a cause or as factor in 147 accidents by the National Transportation Safety Board. These 'vortex-related' accidents have been studied and categorized (by flight phases of the vortex-generating aircraft and the accident aircraft, and other pertinent factors) in the report with the objective of providing historical insight to the Wake Vortex Avoidance System development program. The vortex problem was found to be largely confined to small general aviation aircraft landing or taking off close behind air carrier aircraft under VFR conditions.

Gurke, T. and Lafferton, H.

"THE DEVELOPMENT OF THE WAKE VORTICES WARNING SYSTEM FOR FRANKFURT AIRPORT, PART I: THEORY AND IMPLEMENTATION"

ATCQ07A7, April 1997, DFS Deutsche Flugsicherung, Frankfurt, German.

A Wake Vortices Warning System (WVWS) was identified as a candidate means for increasing the capacity of Frankfurt Airport. For certain meteorological conditions the WVWS is expected to allow for the suspension of wake vortex separation between aircraft approaching the two parallel runways 25. At present, the close vicinity of these parallel runways does not allow wake-vortex-independent operations as a standard procedure. The task of the WVWS is to model the propagation of wake vortices produced in the atmospheric boundary layer by aircraft approaching the runways 25L and 25R and to forecast the wake vortex transport, which is influenced mainly by the crosswind. The predicted propagation of wake vortices is used to determine the risk for approaching aircraft produced by wake vortices generated in the vicinity of the parallel runway system 25L and 25R. On the basis of this hazard prediction, an appropriate landing/operational procedure will be recommended to the controller.

Gurke, T. and Lafferton, H.

"THE DEVELOPMENT OF THE WAKE VORTICES WARNING SYSTEM FOR FRANKFURT AIRPORT: THEORY AND IMPLEMENTATION"

Air Traffic Control Quarterly, Vol. 5, No. 1, 1997, pp. 3-29

A Wake Vortices Warning System (WVWS) has been identified as a candidate means for increasing the capacity of Frankfurt Airport. For certain meteorological conditions, the WVWS is expected to allow for the suspension of required wake vortex separations between aircraft approaching the airport's two parallel runways 25L and 25R. At present, the proximity of these parallel runways does not allow wake-vortex independent operations as a standard procedure. The task of the WVWS is to model the propagation of wake vortices produced in the atmospheric boundary layer by aircraft approaching the runways, and to forecast the wake vortex transport, which is influenced mainly by the crosswind. This predicted propagation of the wake vortices is used to determine the risk for approaching aircraft that is produced by wake vortices generated in the vicinity of the two runways. On the basis of this hazard prediction, an appropriate landing/operational procedure is recommended to the controller. This paper presents the project history, the basic theory and algorithms of the WVWS, the landing procedures for operational use of the system, the WVWS design and implementation, and the testing and evaluation of the system.

Gursul, I.

"REVIEW OF UNSTEADY VORTEX FLOWS OVER SLENDER DELTA WINGS"

Journal of Aircraft, Vol. 42, No. 2, March-April 2005, pp. 299-318.

A wide range of unsteady phenomena relevant to slender vortex flows over stationary and maneuvering delta wings is reviewed. The origin, characteristics, and physical mechanisms of these unsteady phenomena and their role in buffeting are discussed. Dynamic response of leading-edge vortices for maneuvering wings and mechanisms of hysteresis and time lag effects are reviewed. Issues and challenges for unsteady vortex flows over delta wings are outlined.

Gursul, I. and Rockwell, D.

"VORTEX STREET IMPINGING UPON AN ELLIPTICAL LEADING EDGE"

Journal of Fluid Mechanics, Vol. 211, 2006, pp. 211-242.

The interaction of a Karman vortex street with an elliptical edge is investigated experimentally. Basic types of interaction, as a function of scale and transverse displacement of the incident vortex street, are revealed using flow visualization. Unsteady pressure fields induced by these interactions are measured by a phase-averaging technique and correlated with the visualized flow patterns for basic classes of interactions. For a generic vortex-edge interaction, measurements of the phase-averaged velocity field allow construction of streamlines and vorticity contours showing the details of the interaction, including distortion of the vortical structures near the edge. The pressure field is calculated from the measured velocity field and interpreted in relation to the vortical structures. Simulation of

flow visualization using the measured velocity field demonstrates possible misinterpretations related to the underlying vorticity field.

Gursul, I. and Wang, Z.

"FLOW CONTROL OF TIP/EDGE VORTICES"

AIAA Journal, Vol. 56, No. 5, May 2018, pp. 1731-1749.

Location, strength, and structure of tip and edge vortices shed from wings and bodies can be manipulated by using flow control techniques. Flow physics of these approaches involve flow separation from the edge, roll-up into the vortex, wing flow region, vortex instabilities, vortex-vortex interactions, and vortex-turbulence interactions. Actuators include continuous and unsteady blowing as well as suction, bleed, and control surfaces, which add momentum, vorticity, and turbulence into the vortices. It is noted that activation may have effects on more than one aspect of the flow phenomena. A comparative review of the control of delta-wing vortices, tip vortices, and afterbody vortices is presented. The delay of vortex breakdown and the promotion of flow reattachment require different considerations for slender and non-slender delta wings and may not be possible at all. Tip vortices can be controlled to increase the effective span, to generate rolling moment, to alternate wing rock, and to attenuate vortex-wing interactions. Although there are different approaches for each application, opportunities for future research on turbulence injection, bleed, and excitation of vortex instabilities exist. Recent research also indicates that active and passive flow control can be used to manipulate the afterbody vortices to reduce the drag.

Gursul, I. and Xie, W.

"ORIGIN OF VORTEX WANDERING OVER DELTA WINGS"

J. Aircraft, Vol. 37, No. 2, March-April 2000, pp. 348-350

This Note investigates the origin of the vortex wandering over delta wings. The rms swirl velocity in the vortex core is small when the shear layer does not exhibit the K-H instability at low Reynolds numbers. However, the shear layer is dominated by the vortical structures due to the K-H instability for Reynolds numbers larger than a critical value. The corresponding rms swirl velocity in the vortex core becomes much larger, confirming much increased levels of vortex wandering. The present results demonstrate that the vortex wandering is directly related to the presence of the vortical structures in the shear layer due to the K-H instability. This is explained by the Biot-Savart induction of the small-scale vortices, which displace the primary vortex. Nonlinear interactions of small vortices and the primary vortex lead to the random displacements of the primary vortex core.

Gursul, I., Vardaki, E., Margaris, P. and Wang, Z.

"CONTROL OF WING VORTICES"

Active Flow Control, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 95, 2007, pp. 137-151.

Vortex control concepts employed for slender, non-slender and high aspect ratio wings were reviewed. For slender delta wings, control of vortex breakdown has been the most important objective, which is achieved by modifications to swirl level and pressure gradient. Delay of vortex breakdown with the use of control surfaces, blowing, suction, high-frequency and low-frequency excitation, and feedback control was reviewed. For non-slender delta wings, flow reattachment is the most important aspect for flow control methods. For high aspect ratio wings, vortex control concepts are diverse, ranging from drag reduction to attenuation of wake hazard and noise, which can be achieved by modifications to the vortex location, strength, and structure, and generation of multiple vortices.

Guruswamy, G. P.

"INTERACTION OF FLUIDS AND STRUCTURES FOR AIRCRAFT APPLICATIONS"

Computers and Structures, Vol. 30, Issues 1-2, 1988, pp. 1-13

Strong interactions occur between the flow about an aircraft and its structural components, which result in several important aeroelastic phenomena. These aeroelastic phenomena can significantly influence the performance of aircraft. At present, closed-form solutions are available for aeroelastic computations when flows are in either linear subsonic or supersonic range. However, for complex nonlinear flows containing shock waves, vortices and flow separations, computational methods are still under development. Several phenomena that can be dangerous and can limit the performance of an aircraft are due to the interaction of these complex flows with flexible aircraft components such as wings. For example, aircraft with highly swept wings experience vortex-induced aeroelastic oscillations. The simulation of these complex aeroelastic phenomena requires coupling the fluid and structural analysis. This paper provides a summary of the development of such coupled methods and their applications to aeroelasticity. Results based on the transonic small perturbation equations and the Euler equations are presented.

Gustafson, W. A., Davis Jr., D. W. and Deffenbaugh, F.

"ANALYSIS OF THE TURBULENT WAKE OF A CASCADE AIRFOIL"

Journal of Aircraft, Vol. 14, No. 4, April 1977, pp. 350-356

The structure of the wake in an incompressible, turbulent fluid behind an airfoil in a cascade is investigated. Boundary-layer equations containing longitudinal curvature terms are applied to the problem and the similarity properties of the equations are developed. Local similarity solutions are determined for mean velocity profiles at several wake positions, and these results are compared with experimental data for two incidence angles. Good correlation between theory and experiment is obtained beyond approximately a tenth of a chord downstream of the airfoil at small incidence angles.

Gutierrez, E., Quinn, D. B., Chin, D. D. and Lentink, D.

"LIFT CALCULATIONS BASED ON ACCEPTED WAKE MODELS FOR ANIMAL FLIGHT ARE INCONSISTENT AND SENSITIVE TO VORTEX DYNAMICS"

Bioinspiration and Biomimetics, Vol. 12, No. 1, 2017, pp. 016004-1 to 016004-15.

There are three common methods for calculating the lift generated by a flying animal based on the measured airflow in the wake. However, these methods might not be accurate according to computational and robot-based studies of flapping wings. Here we test this hypothesis for the first time for a slowly flying Pacific parrotlet in still air using stereo particle image velocimetry recorded at 1000 Hz. The bird was trained to fly between two perches through a laser-sheet wearing laser safety goggles. We found that the wingtip vortices generated during mid-downstroke advected down and broke up quickly, contradicting the frozen turbulence hypothesis typically assumed in animal flight experiments. The quasi-steady lift at mid-downstroke was estimated based on the velocity field by applying the widely used Kutta-Joukowski theorem, vortex ring model, and actuator disk model. The calculated lift was found to be sensitive to the applied model and its different parameters, including vortex span and distance between the bird and laser sheet -- rendering these three accepted ways of calculating weight support inconsistent. The three models predict different aerodynamic force values mid-downstroke compared to independent direct measurements with an aerodynamic force platform that we had available for the same species flying over a similar distance. Whereas the lift predictions of the Kutta-Joukowski theorem and the vortex ring model stayed relatively constant despite vortex breakdown, their values were too low. In contrast, the actuator disk model predicted lift reasonably accurately before vortex breakdown, but predicted almost no lift during and after vortex breakdown. Some of these limitations might be better understood, and partially reconciled, if future animal flight studies report lift calculations based on all three quasi-steady lift models instead. This would also enable much needed meta studies of animal flight to derive bioinspired design principles for quasi-steady lift generation with flapping wings.

Haans, W., Sant, T., van Kuik, G. and van Bussel, G.

"MEASUREMENT AND MODELLING OF TIP VORTEX PATHS IN THE WAKE OF A HAWK UNDER YAWED FLOW CONDITIONS"

AIAA Paper No. 2005-0590, Reno, NV, January 2005

Tip vortex locations have been measured in the wake of a model rotor in both axial flow and yaw using quantitative flow visualization. For each setting, the axial force coefficient has been derived as well from measurements. The results seem to agree well with those previously published on the Delft University of Technology model rotor. The main interest is to determine the tip vortex pitch, wake skew angle and wake expansion and to physically interpret the data. The results should also help to validate and construct models. The tip vortex locations data complement the existing skewed wake velocity data from hot-wire anemometry, making it a valuable experimental database.

Haans, W., van Kuik, G. and van Bussel, G.

"THE INVERSE VORTEX WAKE MODEL: A MEASUREMENT ANALYSIS TOOL"

Journal of Solar Energy Engineering, Vol. 130, Issue 3, July 2008, pp. 031009-1 to 031009-14.

To reduce the level of uncertainty associated with current rotor aerodynamics codes, improved understanding of rotor aerodynamics is required. Wind tunnel measurements on model rotors contribute to advancing our knowledge on rotor aerodynamics. The combined recording of blade loads and rotor wake is desired, because of the coupled blade and wake aerodynamics. In general, however, the small size of model rotors prohibits detailed blade load measurements; only the rotor wake is recorded. To estimate the experimental blade flow conditions, a measurement analysis tool is developed: the inverse vortex wake model. The rotor wake is approximated by a lifting line model, using rotor wake measurements to reconstruct the vortex wake. Conservation of circulation, combined with the Biot-Savart law, allows the induced velocity to be expressed in terms of the bound circulation. The unknown bound circulation can be solved for, since the velocity is known from rotor wake measurements. The inverse vortex wake model is subsequently applied to measurements on the near wake of a model rotor subject to both axial and yawed flow conditions, performed at a TUDelft open jet wind tunnel. The inverse vortex wake model estimated the unsteady experimental blade load flow conditions and loads that otherwise would have remained obscured.

Haans, W., van Kuik, G. and van Bussel, G.

"THE INVERSE VORTEX WAKE MODEL: A MEASUREMENT ANALYSIS TOOL"

AIAA Paper No. 2007-422, Reno, NV, January 2007.

The aerodynamics of a Horizontal Axis Wind Turbine (HAWT) rotor is of a three-dimensional, unsteady nature and is characterized by strongly coupled blade and wake aerodynamics. To reduce the level of uncertainty associated with current rotor aerodynamics codes, improved physical understanding of rotor aerodynamics is required. Measurements in the near-wake of a model rotor placed in an open jet wind tunnel at the TUDelft aim at increasing knowledge of yawed flow conditions. Detailed blade loads are not measured though. A measurement analysis tool, based on conservation of circulation, is developed that estimates the experimental blade flow conditions: the inverse vortex wake method. The method constructs a vortex wake from measurements, expresses the velocity measured at given points in the wake in terms of unknown bound circulation and solves the overdetermined system of equations for the unknown bound circulation. The unsteady experimental blade flow conditions are estimated for three cases, with yaw angle = 0 degrees, 30 degrees, 45 degrees, using the inverse vortex wake method.

Haas, T. and Meyers, J.

"COMPARISON STUDY BETWEEN WIND TURBINE AND POWER KITE WAKES"

Wake Conference 2017, Uppsala University, Visby, Sweden, May 2017, In Journal of Physics: Conference Series Vol. 854, 2017, pp. 012019-1 to 012019-7.

Airborne Wind Energy (AWE) is an emerging technology in the field of renewable energy that uses kites to harvest wind energy. However, unlike for conventional wind turbines, the wind environment in AWE systems has not yet been studied in much detail. We propose a simulation framework using Large Eddy Simulation to model the wakes of such kite systems and offer a comparison with turbine-like wakes. To model the kite effects in the flow, a lifting line technique is used. We investigate different wake configurations related to the operation modes of wind turbines and airborne systems in drag mode. In the turbine mode, the aerodynamic torque of the blades is directly added to the flow. In the kite mode, the aerodynamic torque of the wings is directly balanced by an opposite torque induced by on-board generators; this results in a total torque on the flow that is zero. We present the main differences in wake characteristics, especially flow induction and vorticity fields, for the depicted operation modes both with laminar and turbulent inflows.

Habercom, Jr., G. E.

"AIRCRAFT WAKE VORTICES - A BIBLIOGRAPHY WITH ABSTRACTS"

PB-82-809112, June 1982, NTIS, Springfield, VA

Wake vortices and turbulent flow across aircraft lifting surfaces were investigated in the Government-sponsored research. Aerodynamic characteristics of vortices were reviewed with special attention made to trailing aircraft and aviation safety.

Habig, C.

"WAKE TURBULENCE BEHIND SMALL AIRCRAFT"

Flying Safety, October 1993, pp. 16-18

The wake from an 18,000-pound F-16 could be strong enough to force a 10,500-pound airplane into the ground from 500 feet.

Hackett, J. E.

"VORTEX DIFFUSER"

US Patent 4,190,219, February 1980.

The vortex system behind an aircraft is responsible for more than half of the aircraft drag in cruise flight and sometimes more in other flight conditions. The purpose of the vortex diffuser is to intercept the wing tip vortex just aft of the wing trailing edge, diffuse the trailing vorticity and thereby achieve a reduction in drag. To do this, an airfoil-shaped device is mounted on a trailing boom situated at or near to the wing tip. The airfoil is mounted above the boom at an angle inboard of the vertical. Its height is

a percentage of wing semispan as is also the mean airfoil chord. The aft-mounting feature permits greater drag reduction at high subsonic Mach number and the inboard vane cant provides significant structural relief. In addition to drag reduction by diffusing the wing tip vortex, some reduction in trailing vortex hazard is also obtained.

Hackett, J. E.

"LOCKHEED TECHNICAL EFFORTS IN WAKE TURBULENCE"

Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, Air Force Flight Dynamics Laboratory, AFFDL-TM-75-16-FGC, 1974, pp. 19-27

An overview is presented of the current wake turbulence research being conducted at Lockheed-California and Lockheed-Georgia. The effects of variations in span loading were examined by solving the general vorticity equation through the superposition of Lamb vortices and extended by allowing the eddy viscosity to vary in the downstream direction. The initial Lamb vortex profile was superimposed on various axial flows, and the second order boundary layer equations integrated to demonstrate how the different axial flows affected vortex decay. Results of a fixed-base simulation of a C-130 encountering a vortex were discussed.

Hackett, J. E. and Evans, M. R.

"VORTEX WAKES BEHIND HIGH-LIFT WINGS"

Journal of Aircraft, Vol. 8, No. 5, May 1971, pp. 334-340

At high wing lift coefficients pertinent to STOL operation, the conventional neglect of vortex roll-up effects can lead to errors when calculating downwash at the tail plane and in the presence of ground or wind-tunnel walls. A classical unsteady treatment in the cross-flow plane, which calculates the roll-up of an initial spanwise row of point vortices, has been modified to allow for the influence of the wing. Additional meaning is thereby given to the streamwise length dimension and hence to aspect ratio and sweep. The effects of height-above-ground and of various tunnel heights and widths are discussed. Under certain limited conditions, notably with part-span flaps or too-narrow a tunnel, part or all of the trailing vortex system may move upwards. Consequent changes in the vertical velocity field are additional to conventional estimates, involving only the appropriate image system.

Hackett, J. E. and Evans, P. F.

"NUMERICAL STUDIES OF THREE-DIMENSIONAL BREAKDOWN IN TRAILING VORTEX WAKES"

Journal of Aircraft, Vol. 14, No. 11, November 1977, pp. 1093-1101

Finite-element three-dimensional relaxation methods are used to calculate the development of vortex wakes behind aircraft for a significant downstream distance. The inclusion of a self-induction term in the solution, dependent upon local curvature and vortex core radius, permits calculation of

finite lifetimes for systems for which infinite life would be predicated two-dimensionally. Single-pair, twin-pair, and multiple-pair studies are described. It is found, in single-pair studies, that there is a lower limit to the wavelengths at which the 'Crow'-type of instability can occur. Below this limit, self-induction effects cause the plane of the disturbance waves to rotate counter to the vortex direction. Self-induction in two-dimensionally generated twin spiral waves causes an increase in axial length, which becomes more marked with decreasing initial wavelength and the time taken for vortex convergence toward the center plane is correspondingly increased. In many cases designed to produce early vortex convergence at the center plane, it is found that the surviving vortex is sufficiently strong for significant hazard to remain. Such cases, which have low flap span, are also characterized by long-wavelength spirals, for which the potential for self-induced wake dispersion is small. There may therefore be a mal-optimum flap-span ratio, in the mid-semispan range, for which time-to-converge maximizes. Limited studies of Boeing 747 configurations show correct qualitative response to removal of the outer flap and to gear deployment, as compared with wind-tunnel and flight-test experience.

Hackett, J. E. and Theisen, J. G.

"VORTEX WAKE DEVELOPMENT AND AIRCRAFT DYNAMICS"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 243-263

Calculations of the sinuous instability of a trailing pair are extended, using a nonlinear vortex modeling technique, and the effects of initial parameters are examined, particularly the initially assumed wavelengths. More complex modes of vortex decay may be demonstrated by flow visualization in water, using the hydrogen bubble technique; vortex bursting is shown to be possible before and/or after the 'wavy' mode. These small-scale measurements are shown to be consistent with flight measurements. In another series of experiments, smoke injected into the core of the trailing vortex behind a 13-foot-span C-130 wind-tunnel model, mounted in a 23-foot by 16-foot working section, showed remarkable coherence until the adverse pressure gradient in the wind-tunnel diffuser caused vortex bursting. The results of a computer simulation are discussed concerning the dynamic response and loads on an aircraft which enters the trailing vortex of a lead aircraft of large size.

Hackett, J. E., Scruggs, R. M., Lyman, V. and Theisen, J. G.

"THEORETICAL ANALYSIS AND DATA INTERPRETATION TO ASSIST THE GOVERNMENT IN EVALUATING THE VARIOUS DEVICES PROPOSED FOR ENHANCING VORTEX DECAY AND EXTRAPOLATION OF LABORATORY RESULTS TO FULL-SCALE APPLICATION"

Report LG74ER0152, October 1974, Lockheed-Georgia, Marietta, GA

The efforts briefly described herein evaluated methods for alleviating the aircraft vortex wake hazard problem. Lockheed-Georgia Company scientists and consultants have used both theoretical means (hopefully to predict a physical mechanism for causing premature vortex decay) and correlation with IR&D scaled model tests on aero-mechanical devices or energizing techniques (vortex generators, jets, etc.) to modify the vortex wake without unacceptable compromise in aircraft performance. Principal

tasks include: a) Theoretical study of jet and wake effects on vortex decay; b) Provide span-load distributions for Boeing 747 using potential flow model; c) Study the distortion of a vortex by a lifting surface immersed in the vortex; d) Feasibility study of using a vortex roll-up program iteratively with a vortex-lattice program to determine mutual interaction effect; e) Continuing consultation on a moving-base simulator program at NASA (Ames) jointly with the FAA.

Haefele, A., Barras, E. M., Maier, O., Ruffieux, D. and Calpini, B.

"COMPOSITE TEMPERATURE PROFILES FROM RAMAN LIDAR AND MICROWAVE RADIOMETER"

9th International Symposium on Tropospheric Profiling (ISTP), September 2012, University of L'Aquila, L'Aquila, Italy.

We present two methods to combine Raman lidar and microwave radiometer for profiling atmospheric temperature. The Raman lidar provides profiles with high vertical resolution, but needs frequent calibration with an external measurement. The microwave radiometer provides an accurate measurement of the absolute value of the atmospheric temperature, though, with a coarse vertical resolution. Approach 1 consists of two steps: first, recalibration of the lidar using the radiometer data, and second, merging of the recalibrated lidar profile with the radiometer profile. We show that this approach is capable to correct for instabilities of the lidar system and provide a smooth composite temperature profile. In approach 2 the microwave spectrum measured by the radiometer is inverted applying an optimal estimation method using the lidar measurement as a priori profile. The result is a smooth temperature profile based on the optimized use of the available information.

Haertig, J., Rey, C. and Havermann, M.

"PIV MEASUREMENTS OF COMPRESSIBLE VORTEX RINGS GENERATED BY A SHOCK TUBE"

13th International Symposium on Applied Laser Techniques to Fluid Mechanics, June 2006, Lisbon, Portugal.

In this study, fast propagating vortex rings were generated with a small shock tube. The vortex rings were visualized by the laser light sheet and the instantaneous velocity field measured by a 2D-PIV system. The vortex core can be well defined and the streamlines in the vortex ring are visible from the velocity field measurement. The measurements also yield information about the vorticity and the kinetic energy within the vortex ring. The evolution of these values along the ring's propagation path can be compared with existing theories of incompressible vortex rings.

Hageraats, W. A.

"FLUID DYNAMIC SIMULATIONS OF VORTEX-JET INTERACTION"

MS Thesis, Delft University of Technology, Delft, The Netherlands, April 2006

To support towing tank measurements as part of the FAR-WAKE project and to gain knowledge about vortex-jet interaction, simulations are performed using CFD analysis. For this purpose, a generic fuselage-wing model (SWIM model) is used at an angle of attack of 6 degrees and in an uniform free stream velocity of 60 m/s. The main objective of this investigation is to examine the impact of jet with uniform jet velocity on the evolution of the trailing vortex system. The CFD experiments have been benchmarked with wind tunnel data that was obtained for the SWIM model without the application of a jet. This data was collected by the NLR by means of PIV and rake measurements. For the vortex-jet interaction studies it was chosen to use the dimensions of the DNW-LST wind tunnel to model the flow numerically. As the domain of interest extends from the near field behind the model all the way to the far field, it was necessary to simplify the CFD calculations. First, the computational domain has been divided into a 3-dimensional steady part that simulates the roll-up process until all significant streamwise flow gradients have disappeared and an unsteady 2-dimensional part more aft of the body capturing the quasi-2-dimensional behavior, characteristic for the vortex flow in this part of the wake. Other simplifications involve the modeling of a laminar flow condition and omission of several instabilities known to occur in the far field behind the model. Results obtained show that the effect of a laminar jet on the evolution of the vortex wake is small.

Hahn, D., Scholz, P. and Radespiel, R.

"VORTEX GENERATION IN A LOW SPEED WIND TUNNEL AND VORTEX INTERACTIONS WITH A HIGH-LIFT AIRFOIL"

AIAA Paper No. 2012-3024, June 2012, New Orleans, LA.

This paper describes the design, construction and evaluation of a vortex generator in a closed wind tunnel, with the objective to produce well defined disturbances convecting over a high-lift airfoil. The vortex generator produces quasi two-dimensional vortices in transverse direction. The design criteria, the mode of use and the framework of the vortex generator are described. Furthermore, the produced vortices and their propagation are characterized along an otherwise empty test-section as well as their interaction with a high-lift airfoil. To acquire the presented data, several measurement methods, such as Particle Image Velocimetry (PIV), a newly developed time resolving Five Hole Probe (FHP), monitoring the position of the servo-actuators and time resolving as well as static pressure measurements were used. As a result, the vortex generator's ability to create reproducible single vortices, as well as reproducible series of vortices, has been verified.

Hahn, K.-U.

"COPING WITH WAKE VORTEX"

ICAS-2002-7.3.2, Toronto, Canada, September 2002

The hazardous area around a wake vortex can be approximated by the simple geometry of a rectangle or an ellipse according to aircraft pairing, weather dependent decay and available roll control power.

Using specific controllers, vortices can be passed through even if the required control power temporarily exceeds available capacity.

Hahn, K.-U.

"WAKE VORTEX ENCOUNTER AVOIDANCE COMPUTATION OF SAFE AIRCRAFT SEPARATIONS USING THE SHAPE CONCEPT"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

This presentation introduces a concept of wake vortex encounter avoidance using the Simplified Hazard Area Prediction (SHAPE) concept. This approach is based on the definition of a hazard zone around a wake vortex derived from quasi-steady considerations. SHAPE is an element in the Wake Vortex Prediction and Observation System which is under development in the frame of the DLR 'Wake Vortex II' project to reduce aircraft approach separation and to improve flight safety. In any case, the separation distance of approaching aircraft must be established in such a way that no dangerous wake vortex flow will be encountered. This results in the demand that the approach corridor is free of hazardous flow conditions for an approaching aircraft. The question to be answered is what is the meaning of 'hazard free'? Therefore, many investigations and simulator studies have been set up and executed with the aim to find a universal criterion for the definition of wake vortex encounter constraints being hazardous to an aircraft. Although impressive progress has been made it could not be expected that an exact prediction will be possible if an encounter will be hazardous or not. Accepting this fact that a clear criterion of what is hazardous (in terms of encounter boundaries and constraints leading unquestionably into an unsafe situation) is difficult to set up (especially if a pilot is in the loop) an 'inverse' approach of hazard definition is proposed. The presented approach for solving the fundamental hazard assessment problem follows the idea that it is easy to define an area around a wake vortex outside of which the vortex flow is not hazardous to an aircraft. This methodology is more a non-hazard concept than a real safety assessment method. But it seems to be very promising in terms of operational application. The worst-case situation can be assumed to be a wake vortex parallel to the glide path with permanent demand for roll moment compensation. In that quasi-steady case, the threat can easily be calculated from the required control power expressed in terms of normalized aileron deflections. A certain fraction of this expression is identified to present a safe limit in terms of wake vortex encounter depth. The resulting boundaries of the hazardous area to be avoided are investigated by numerous offline simulations.

Hahn, K.-U. and Schwarz, C.

"ALLEVIATION OF ATMOSPHERIC FLOW DISTURBANCE EFFECTS ON AIRCRAFT RESPONSE"

ICAS 2008, September 2008, Hamburg, Germany.

This paper gives an overview of the results of offline simulations, full flight simulator studies and results from in-flight simulation experiments to investigate the alleviation of atmospheric flow

disturbance effects on aircraft response. Gusts and turbulence strongly affect the passenger comfort and the safety of aircraft. Another important air mass motion adversely affecting aircraft operations is wake vortex. This well-known hazardous flow field is produced by aircraft themselves. Active control technology can be applied to alleviate these flow disturbance effects on aircraft motion in case of an encounter. It can be shown that the aircraft response encountering natural and aircraft-induced (wake vortex) turbulence can be improved significantly by a feed-forward controller. Based on a forward-looking sensor, the controller generates aerodynamic surface deflections to counter the vertical accelerations generated by gusts as well as the roll response induced by the lift variations along the wing span. For this investigation it is assumed that a LIDAR sensor can provide the necessary flow field information ahead of the aircraft. In addition to the standard control surfaces (elevator, aileron, and rudder) the aircraft is supposed to be equipped with special flaps for independent direct lift control.

Hahn, K.-U. and Schwarz, C. W.

"WAKE VORTEX AVOIDANCE VERSUS LANDING CAPACITY"

AIAA Paper No. 2006-6322, Keystone, CO, August 2006

Wake vortex separations are limiting factors in landing capacity of airports. The increasing air traffic forms the need for more flexible separation procedures considering the actual weather situation and the parameters of a more individual aircraft pairing. The present separation standards must be investigated carefully with the aim to discover possible margins by improving the limiting constraints without adverse effects on safety. Separation reductions can also be achieved by wake vortex avoidance using prediction systems for the wake related hazard zones their development and movement. Avoiding these zones allows safe and undisturbed flight operations. The definition of a reliable and validated safety criterion is the fundamental element for the determination of hazard areas. The presented definition is based on the normalized required roll control power of the encountering aircraft. For manually controlled aircraft the limit of the acceptable normalized roll control power can be established using full flight simulator studies and in-flight simulations. Parameterization of the relevant parameters leads to the universally applicable concept of the 'Simplified Hazard Area Prediction' method (SHAPE), SHAPE provides the hazard area dimensions for specific approach situations. SHAPE is part of a Wake Vortex Prediction and Monitoring System developed within the DLR project Wirbelschlepp II for creating safe and reduced landing operations. Some general results for specific approach conditions on a single runway are presented.

Hahn, K.-U. and Schwarz, C. W.

"SAFE LIMITS FOR WAKE VORTEX PENETRATION"

AIAA Paper No. 2007-6871, August 2007, Hilton Head, SC.

The strength of the vortices increases with the weight of the vortex generating aircraft. Therefore, weight dependent separation distances have been established to avoid dangerous wake vortex encounters. To solve the future capacity problems at airports, these proven separation distances must

be investigated carefully with the aim to discover possible margins. This demand forms the need for more flexible separation procedures considering the actual weather situation and the parameters of the individual aircraft pairing. In any case the separation distance of approaching aircraft must be determined in such a way that the approach corridor is free of hazardous vortex flows for the trailing aircraft. The question to be answered is what is the meaning of 'hazard free', respectively how close is an aircraft allowed to approach a vortex without adversely affecting undisturbed flight operation? The determination of a reliable threshold is only possible with pilot-in-the-loop investigations. This paper presents the results of flight simulator studies and in-flight simulations using real flight test aircraft. Based on the required normalized roll control power tolerable and safe situations can be distinguished from unacceptable encounters and a threshold value can be established. The tolerable threshold value can be increased if the pilots control task is supported by an automatic controller.

Hahn, K.-U., Fischenberg, D., Niedermeier, D. and Horn, C.

"WAKE ENCOUNTER FLIGHT CONTROL ASSISTANCE BASED ON FORWARD-LOOKING MEASUREMENT PROCESSING"

AIAA Paper No. 2010-7680, Toronto, Canada, August 2010.

Weather dependent delays, incidents and even accidents play an important role in aircraft operation. Any airplane is subject to air motion. Thus, turbulence is an important parameter in aeronautics. The phenomena which are summarized as gusts and turbulence strongly affect the passenger comfort and the safety of aircraft. Especially the turbulence caused by the wake of other aircraft can cause undesired motions mainly roll and vertical displacements. Active control technology can be applied to alleviate wake vortex effects on aircraft and support the pilot to carry out his control task. With the aid of specific controllers such vortices can be safely encountered even if the required control power temporarily exceeds the available capacity. Aircraft equipped with such a controller will be less affected by unforeseen wake vortex encounters or even will be able to follow another aircraft closer than authorized by the current separation distances without any compromise concerning safety. A very promising concept for wake vortex disturbance alleviation is the feed-forward disturbance compensation. The application of such an approach requires the accurate determination of the flow disturbance to calculate the necessary counter measures in terms of required control activities. Thus, the disturbance flow determination plays an important role and needs to be investigated thoroughly. Modern LIDAR technology has the potential to measure the flow field in front of the aircraft and to provide the required disturbance information in advance before it affects the aircraft. The final goal of the DLR approach is the development of an Integrated Ride and Loads Improvement System which is able to cope with the whole frequency range of atmospheric flow disturbances relevant for aircraft operation.

Hahn, K.-U., Schwarz, C. and Friehmelt, H.

"A SIMPLIFIED HAZARD AREA PREDICTION (SHAPE) MODEL FOR WAKE VORTEX ENCOUNTER AVOIDANCE"

ICAS-2004, Yokohama, Japan, September 2004

This paper gives details from offline simulations, full-flight simulator studies and the preparation of a flight test experiment using the In-Flight Simulation capability of DLR's (German Aerospace Center) test aircraft ATTAS (Advanced Technologies Testing Aircraft) to validate safe boundaries around a wake vortex for encounter avoidance. The so developed hazard zone is an element in the Wake Vortex Prediction and Observation System which is under development in the frame of the DLR 'Wake Vortex II' project to reduce aircraft approach separation and to improve flight safety. In any case the separation distance of approaching aircraft must be determined in such a way that the approach corridor is free of hazardous vortex flows for the trailing aircraft. The question to be answered is what is the meaning of 'hazard free'? The presented approach for solving this fundamental problem follows the idea that it is possible to define an area around a wake vortex outside which the vortex flow is not hazardous to an aircraft. The reason for this 'inverse' definition is the fact that a clear criterion of what is hazardous is difficult to set up (especially if a pilot is in the loop). The so defined boundaries of the hazard zone can easily be determined by the developed Simplified Hazard Area Prediction (SHAPE) Model. It allows the computation of hazard zone dimensions for any aircraft pairing (real or non-existing aircraft). This potential of a universal application is based on the parameterization of the relevant aircraft wake vortex characteristics which are fitted by simple functions.

Haider, J.

"DESIGN OF WINGTIP VORTEX TURBINE"

ICAS 2000, August 2000, Harrogate, UK.

During lift the pressure difference across upper and lower sides of the aircraft wing, forces the flow of air to curl around the wing tip resulting in wing tip vortices which in turn creates induced drag. Induced drag has been a great problem of all the aircraft and at times it reaches up to 70 percent of the total drag. The idea of wing tip turbine is to use the energy of the vortices to generate extra power thus reducing induced drag at the same time. However total drag would increase due to profile drag of the turbine. To cater it, this design has been done such that the drag created by turbine in a particular phase should not exceed the induced drag reduced by the turbine. In this way maximum energy is extracted without paying the penalty of drag. The theoretical study is based upon drag type turbine installed on NACA 2418 airfoil whose specifications bear geometric similarity to the wing of T-37 aircraft. The experimental results are based upon the wind tunnel testing of the scale down model of the assumed wing.

Haines, A. L.

"CONCEPTS FOR DETERMINATION OF LONGITUDINAL SEPARATION STANDARDS ON FINAL APPROACH"

MTR-7047, October 1975, Mitre Corp., McLean, VA

The concept of a longitudinal separation standard on final approach requires precise definitions to develop an analytical structure. These are developed in this paper with a view toward identifying the

relationships between separation standards and the variables describing the final approach environment. This provides a basis for systematic evaluation of changes in separation standards due to changes in the environment, particularly through Engineering and Development products. Analytical relationships are developed primarily for IFR conditions, represented by strict adherence to all applicable ATC rules and procedures. For modeling purposes, relationships are also developed for 'standards' for VFR conditions, represented by visual approaches from an IFR flight plan.

Hall, C. M.

"HIGH-ORDER ACCURATE SIMULATIONS OF WAKE AND TIP VORTEX FLOWFIELDS"

MS Thesis, Dec. 1998, Penn State University, University Park, PA.

Accurate simulation of rotorcraft wakes and blade-vortex interaction continues to be a challenge. Of particular importance is the numerical diffusion of vorticity, which has yet to be alleviated sufficiently. One solution to this problem may be the use of numerical algorithms which exhibit very low dissipation. This thesis investigates the use of high-order, unsteady computational fluid dynamics for the simulation of flows dominated by vorticity. A code has been developed which solves the unsteady, three-dimensional Euler equations using explicit, fourth-order Runge Kutta time integration and fourth-order spatial differencing. Similar to dispersion relation preserving methods, this algorithm was chosen for its favorable numerical characteristics regarding dissipation. The effectiveness of the high-order algorithm is demonstrated on two model problems -- vortex convection and near-wake development. Simulations of a line vortex have been carried out to a convection distance of 2000 core radii, much farther than has been found in the literature to date. Studies on the effects of grid density and uniformity across the vortex core have been made, allowing estimates of global grid size for complete rotorcraft wake simulation.

Hall, D. L. and Amodeo, F. A.

"OPPORTUNITIES ANALYSIS OF POTENTIAL ADVANCED VORTEX SYSTEMS SEPARATION STANDARDS"

FAA-EM-79-17, July 1979, Mitre Corp., McLean, VA

The purpose of this study is to provide first order estimates of the benefits of reduced separation standards under Advanced Vortex System (AVS) operations. Benefits associated with conceptual Advanced Vortex Systems (AVS) are quantified from a delay reduction viewpoint. The study is equally applicable to airborne vortex alleviation technology or to ground or air-based vortex avoidance systems. Conducted as a first cut, exploratory analysis, the research compares the delay consequences of three sets of successively closer interarrival standards against the option of maintaining today's rules or a combination of today's and 3 nmi separations. The analysis was performed for only IFR weather conditions, since minimum required separation standards are not defined for VFR conditions. Three sets of standards were selected as representative of possible AVS capabilities. Substantial delay savings are shown to be possible even with demand growth below that projected to occur across the 1985

through 1995 analysis time-period. The benefits are sufficiently large as to warrant a substantial research and development investment into an AVS program.

Hall, J. L.

"AN INTRODUCTION TO VORTEX BREAKDOWN AND VORTEX CORE BURSTING"

NRC-24336, March 1985, National Aeronautical Establishment, Ottawa, Ontario, Canada

The phenomenon of vortex breakdown, also known as vortex core bursting, is introduced. The first part of the report presents some important elements of basic vortex theory. The second part reviews the research that was done on vortex breakdown. An overview of the historical development of vortex breakdown research and a summary of the current state of knowledge on the subject are also included.

Hall, M. G.

"A NEW APPROACH TO VORTEX BREAKDOWN"

Proceedings of 1967 Heat Transfer and Fluid Mechanics Institute, edited by P. Libby, D. Olfe and C. Van Atta, Stanford Univ. Press, 1967, pp. 319-340

Comparison between a practical example of vortex breakdown and a computed failure of the quasi-cylindrical approximation, and description of evidence that failure corresponds to breakdown. The theory for viscous axisymmetric quasi-cylindrical flows including the governing equations and boundary conditions, and the numerical method of solving the equations, is outlined. A simple model of a vortex core is set up which depends on only two parameters, representing the magnitude of the swirl and the shape of the bounding stream surface.

Hall, M. G.

"VORTEX BREAKDOWN"

Annual Review of Fluid Mechanics, Vol. 4, Ann. Rev. Inc., Palo Alto, CA, 1972, pp. 195-218

A study was made of the breakdown feature of the vortex core. The vortex core was set up by drawing fluid through a duct and imparting swirl with a set of vanes at entry. The spiral was followed along the duct and it was found that the structure of the vortex varied slowly in the axial direction, and then, unexpectedly, there is an abrupt change in the structure with a very pronounced retardation of the flow along the axis and a corresponding divergence of the stream surfaces near the axis.

Hall, M. G.

"A NUMERICAL METHOD FOR SOLVING THE EQUATIONS FOR A VORTEX CORE"

ARC-R&M-3467, May 1965, Royal Aircraft Establishment, Farnborough, England

A method is presented for calculating steady axially symmetric spiraling motions of an incompressible fluid at large Reynolds numbers. By making approximations of the boundary-layer type the Navier-Stokes equations are reduced essentially to a pair of non-linear parabolic equations. Initial conditions are specified on some upstream cross-section, and boundary conditions on the axis of symmetry and on some bounding surface of revolution.

Hall, M. G.

"THE STRUCTURE OF CONCENTRATED VORTEX CORES"

Progress in the Aeronautical Sciences, Vol. VII, edited by D. Kucheman, Pergamon Press, 1966, pp. 53-110

In a vortex we often observe an approximately axially symmetric core of spiraling fluid in which the vorticity is high. A review is given of recent work on the structure of such vortex cores. It begins with a discussion of the equations of motion and the appropriate boundary conditions, and continues with a description in general terms of the vigorous but highly responsive character of the flow, of the effects of compressibility and turbulence and of the phenomenon of energy separation. A discussion is given of the phenomenon of stagnation in the axial flow, spiral instability, and finite transition, any of which may destroy the typical core of high vorticity or prevent its maintenance.

Hall, M. G.

"A THEORY FOR THE CORE OF A LEADING-EDGE VORTEX"

J. Fluid Mech., Vol. 11, Part 2, September 1961, pp. 209-228

In the flow past a slender delta wing at incidence one can observe a roughly axial symmetric core of spiraling fluid, formed by the roll-up of the shear layer that separates from a leading edge. The aim of this paper is to predict the flow field within this vortex core, given appropriate conditions at its outside edge. A sample calculation yields results which are in good qualitative and fair quantitative agreement with experimental measurements.

Hall, T. and Soares, M.

"ANALYSIS OF LOCALIZER AND GLIDE SLOPE FLIGHT TECHNICAL ERROR"

27th Digital Avionics Systems Conf., St. Paul, Minn., Oct. 2008

A new wake turbulence procedure has been developed that permits two dependent arrival traffic streams during instrument meteorological conditions (IMC) to runways with centerline separations less

than 2500 ft. For the proposed procedure, aircraft approaching both runways of a closely-spaced pair under limited ceiling/visibility conditions utilize Instrument Landing System (ILS) localizer and glide slope guidance. A critical safety analysis building block was to quantify the risk posed by aircraft Flight Technical Error (FTE), a measure of the deviations from the localizer/glide slope centerlines, under ceiling/visibility conditions when non-visual ILS approaches are normally performed. Flight track data from Lambert-St. Louis International Airport (STL) under severe IMC conditions, when strict adherence to navigation aide guidance would most likely occur, were used to quantify the aircraft dispersion characteristics. The position sensors were the STL Airport Surface Detection Equipment, Model X (ASDE-X), the on-airport Surface Measurement Radar, multi-lateration subsystem sensors, and by Riegl laser range-measurement sensors near the runway thresholds. In general, the FTE found in this analysis were significantly tighter than the International Civil Aviation Organization navigation tolerances commonly used in safety simulations.

Hall, T., Mackey, S., Lang, S. and Tittsworth, J.

"LOCALIZER FLIGHT TECHNICAL ERROR MEASUREMENT AND UNCERTAINTY"

2011 IEEE/AIAA 30th Digital Avionics Systems Conference, October 2011, Seattle, WA.

Recent US Federal Aviation Administration wake turbulence research conducted at the John A. Volpe National Transportation Systems Center has continued to monitor the representative localizer Flight Technical Error (FTE) associated with ILS arrivals. This work complements, extends, and improves on previously published localizer ILS results by calculating FTE from more recent Airport Surface Detection Equipment -- Model X (ASDE-X) datasets with improved data quality characteristics, as well as providing a quantification of the FTE measurement uncertainty due to the geometry of the Remote Unit sensor array that provides the analysis data. This paper presents additional FTE results and improved uncertainty calculations for ILS arrivals at John F. Kennedy International Airport and Detroit Metropolitan Wayne County Airport, as well as comparisons with previous documented FTE results from Lambert-St. Louis International Airport.

Haller, G.

"AN OBJECTIVE DEFINITION OF A VORTEX"

J. Fluid Mech., Vol. 525, 2005, pp. 1-26

The most widely used definitions of a vortex are not objective: they identify different structures as vortices in frames that rotate relative to each other. Yet a frame-dependent vortex definition is essential for rotating flows and for flows with interacting vortices. Here we define a vortex as a set of fluid trajectories along which the strain acceleration tensor is indefinite over directions of zero strain. Physically, this objective criterion identifies vortices as material tubes in which material elements do not align with directions suggested by the strain eigenvectors. We show using examples how this vortex criterion outperforms earlier frame-dependent criteria. As a side result, we also obtain an objective criterion for hyperbolic Lagrangian structures.

Hallermeyer, A., Dolfi-Bonteyre, A., Valla, M., Le Brusquet, L., Fleury, G., Thobois, L., Carion, J. P., Duponcheel, M. and Winckelmans, G.

"DEVELOPMENT AND ASSESSMENT OF A WAKE VORTEX CHARACTERIZATION ALGORITHM BASED ON A HYBRID LIDAR SIGNAL PROCESSING"

AIAA Paper 2016-3272, June 2016, Washington, DC.

Since air traffic is in constant expansion, a more efficient optimization of the airports' capacity is expected. In this context, the characterization of aircraft hazardous turbulence known as wake vortices with an operational vortex LIDAR is one of the major issues for the dynamic distances' separation. A study has been probed to develop a hybrid vortex algorithm, i.e. that uses both the velocity envelopes and a parametric estimator in the purpose of estimating accurately and precisely the circulations with a processing time as short as possible. The aim is to make this algorithm exploitable for operational projects. That is why a methodology has been set up to evaluate the precision and its robustness. The results of tests on simulated scenarios of different aircraft vortices and different weather conditions including analytical simulations and Large Eddy Simulations show that this algorithm is able to localize precisely wake vortices and to estimate accurately their circulation since the root mean square error is below 20 percent even in the LES case when the vortices have been distorted sometime after the passage of the aircraft.

Hallock, J. N.

"VORTEX ADVISORY SYSTEM SAFETY ANALYSIS, VOLUME III: SUMMARY OF LASER DATA COLLECTION AND ANALYSIS"

FAA-RD-78-68,III, August 1979, DOT Transportation Systems Center, Cambridge, MA.

A Laser-Doppler Velocimeter was used to monitor the wake vortices shed by 5300 landing aircraft at a point 10,000 feet from the runway threshold. The data were collected to verify the analysis in Volume I of the safety of decreasing interarrival separations to three nautical miles between the outer marker and the runway threshold. Such reduced spacings would only be used when the Vortex Advisory System (VAS) indicated that wake vortices would not pose a threat to a following aircraft. The data show that vortex behavior, during times identified by the VAS, is commensurate with the goal of using uniform three-nautical miles separations from the outer marker to touchdown regardless of leader or follower aircraft type.

Hallock, J. N.

"VORTEX ADVISORY SYSTEM SAFETY ANALYSIS, VOLUME I: EFFECTIVENESS FOR SELECTED AIRPORTS"

FAA-RD-80-62,I, May 1980, DOT Transportation Systems Center, Cambridge, M.

The Vortex Advisory System (VAS) is based on a wind criterion; when the wind near the runway end is outside of the criterion, all interarrival IFR aircraft separations can be set at 3 nautical miles. Five years of wind data have been obtained for 20 airports. By comparing the VAS wind criterion to the 5 years of wind data, the percentages of time that interarrival separations can be reduced at the 20 airports have been found. The percentages are given on an hourly and a monthly basis.

Hallock, J. N.

"ANALYSIS OF THE WAKE VORTEX IMPLICATIONS FOR THE PROPOSED LDA/DME APPROACH AT LAMBERT/ST. LOUIS"

FAA-427-PM-84-1, December 1983, DOT Transportation Systems Center, Cambridge, MA

The proposed simultaneous use of ILS approaches to runway 12R and LDA/DME approaches to runway 12L at St. Louis International (Lambert Field) is analyzed from a wake turbulence perspective. Although the two runways are only 1300 feet apart, their staggered thresholds mitigate the wake turbulence problem. To preclude a vortex encounter, certain restrictions must be imposed: all Heavy-category aircraft must be confined to runway 12R, all Small-category aircraft must be confined to runway 12L, no aircraft larger than a B-727 may use runway 12L, and an MDA must be established for the 3-nm DME fix on runway 12L.

Hallock, J. N.

"AIRCRAFT WAKE VORTICES: AN ASSESSMENT OF THE CURRENT SITUATION"

DOT-FAA-RD-90-29, January 1991, DOT Volpe National Transportation Systems Center, Cambridge, MA

The state of knowledge about aircraft wake vortices in the summer of 1990 is summarized. With the advent of a new FAA wake vortex program, the current situation was assessed by answering five questions: (1) what do we know about wake vortices, (2) what don't we know about wake vortices, (3) what are the requirements and limitations for operational systems to solve the wake vortex problems, (4) where do we go from here, and (5) why do we need to collect more wake vortex data.

Hallock, J. N.

"AIRCRAFT WAKE VORTICES: AN ANNOTATED BIBLIOGRAPHY (1923 - 1990)"

DOT-FAA-RD-90-30, January 1991, DOT Volpe National Transportation Systems Center, Cambridge, MA

This annotated bibliography consists of abstracts of publications on aircraft wake vortices. The material is arranged alphabetically by author(s) and then by month and year of publication. Experimental and theoretical articles are included and consider the formation, structure, motion, and decay of vortices and their effect on penetrating aircraft.

Hallock, J. N.

"AIRCRAFT WAKE VORTICES: THEIR MOTION AND DECAY"

AIAA Seminar, Boston University, Boston, MA, January 1973

A review of the physics of aircraft wake vortices was presented considering the formation of vortices and their subsequent motion and decay. The experimental and analytical research programs of the Department of Transportation were reviewed; particular emphasis was given to the effects of meteorology on aircraft wakes.

Hallock, J. N.

"MONITORING THE MOVEMENT OF WAKE VORTICES AT KENNEDY AND STAPLETON AIRPORTS"

Proceedings of the Fifth Annual Symposium of the Society of Flight Test Engineers, SFTE, Anaheim, CA, 1974, pp. 4/7-4/12.

During the summer and fall of 1973, the Transportation Systems Center collected an extensive amount of data on the motion of aircraft wake vortices. Two test sites were instrumented: the John F. Kennedy International Airport in New York and the Stapleton International Airport in Denver, Colorado. The vortices from over 10,000 landing aircraft were recorded and the motion of the vortices correlated with the ambient meteorological conditions. The results of these measurements coupled with user requirements lead to the description of three basic vortex avoidance systems.

Hallock, J. N.

"WAKE VORTEX MODELING AND DETECTION"

Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, Air Force Flight Dynamics Laboratory, AFFDL-TM-75-16-FGC, 1974, pp. 59-63

The FAA program in wake vortices was reviewed and included: the development of reliable vortex prediction methods in terms of meteorological conditions and generator aircraft characteristics, the determination of a hazard criterion regarding how close an aircraft can approach a vortex without experiencing an unacceptable disturbance, and the development of effective vortex detection equipment. The results of over 10,000 vortex observations recorded at Kennedy and Stapleton International Airports were presented as well as possible techniques for eventually decreasing current separation criteria.

Hallock, J. N.

"WAKE VORTEX DECAY NEAR THE GROUND"

AIAA Paper No. 1975-0882, Hartford, CT, June 1975

The strength of wake vortices is being measured for aircraft landing on runway 31R at JFK International Airport using monostatic acoustic radars. By range-gating and Doppler processing the backscattered acoustic energy from several sensors, measurements are made of vortex height, strength or circulation, vertical velocity field, translational velocity, and the circulation distribution within the vortex. Possible decay mechanisms and correlations with meteorological conditions are presented.

Hallock, J. N.

"AIRCRAFT WAKE VORTICES - AN ANNOTATED BIBLIOGRAPHY (1923-1975)"

FAA-RD-76-43, January 1976, DOT Transportation Systems Center, Cambridge, MA

This annotated bibliography consists of 570 abstracts of publications on aircraft wake vortices. The material is arranged alphabetically by year of publication and covers the time period through 1975. Experimental and theoretical articles are included (except for helicopter vortices) and consider the formation, structure, motion, and decay of vortices and their effect on penetrating aircraft.

Hallock, J. N.

"MONITORING WAKE VORTEX STRENGTH DECAY NEAR THE GROUND"

Journal of Aircraft, Vol. 13, No. 10, October 1976, pp. 830-832

The strength of aircraft wake vortices is being measured for aircraft landing on runway 31R at the John F. Kennedy International Airport using monostatic acoustic radars. By range-gating and Doppler processing the backscattered acoustic energy from a number of sensors, measurements are made of vortex height, strength or circulation, vertical velocity field, translational velocity, and the circulation distribution within the vortex. Possible decay mechanisms and correlations with meteorological conditions are described.

Hallock, J. N.

"VORTEX ADVISORY SYSTEM SAFETY ANALYSIS, VOLUME I: ANALYTICAL MODEL"

FAA-RD-78-68,I, September 1978, DOT Transportation Systems Center, Cambridge, M.

An analysis was conducted to examine the safety of decreasing landing aircraft separations to three nautical miles between the outer marker and the runway threshold. Such reduced separations would only be used when the Vortex Advisory System indicated that wake vortices would not pose a threat to a following aircraft. Based on state-of-the-art models of vortex and aircraft behavior, the analysis indicates that such reduced interarrival separations may be used safely by Large and Heavy aircraft following Heavies. When the analysis is expanded to include a yet unproven crosswinds aloft model, the results indicate that reduced separations may be used by all aircraft regardless of leader/follower aircraft type.

Hallock, J. N.

"PRESSURE MEASUREMENTS OF WAKE VORTICES NEAR THE GROUND"

Journal of Aircraft, Vol. 9, No. 4, April 1972, pp. 311-312

A simple barocel pressure sensor was tested to determine whether it could detect the presence of aircraft wake vortices. Pressure differentials more than 0.1 millibars were consistently measured when the vortices from DC-7, B-747, B-707, DC-8, C-141, and DC-3 aircraft were below 100 feet in altitude.

Hallock, J. N.

"DIFFERENCES BETWEEN LANDING AND TAKEOFF WAKE VORTICES"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 81-82

Data on wake vortex behavior from over 70,000 landing and 30,000 departures have been collected and analyzed. This presentation will examine the differences in vortex behavior (motion and decay) between these two regimes. The differences, in some cases, are not what one might expect at first glance. The effects of the winds and vortex altitude on vortex motion (persistence near the runway centerline as well as long distance movement in ground effect) and decay will be presented.

Hallock, J. N. and Burnham, D. C.

"DECAY CHARACTERISTICS OF WAKE VORTICES FROM JET TRANSPORT AIRCRAFT"

AIAA Paper No. 1997-0060, Reno, NV, January 1997

For more than two decades cw doppler lidars have been used to study the decay of wake vortices generated by jet transport aircraft. With appropriate scan and data processing strategies, the vortex tangential velocity profile can be measured every few seconds. Under low turbulence conditions conducive to long vortex persistence the observed decay process is contrary to that predicted by classical theory and observed at low Reynolds numbers in wind tunnels and for small aircraft; namely, that the core grows in size and the maximum tangential velocity decreases while the total circulation remains roughly constant. For full-sized jet transport aircraft, the vortex core often remains stable while the outer portion of the vortex decays, thereby reducing the total circulation. Data are presented from B-747 alleviation flight tests conducted in the 1970s and for other aircraft collected in the early 1990s. The stability of the core is consistent with the essentially laminar core flow observed via flow visualization.

Hallock, J. N. and Burnham, D. C.

"ANALYSIS OF WAKE VORTEX MEASUREMENT DATABASES"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

Many wake vortex databases have been collected and analyzed over the past three decades. Most of these tests were conducted at airports. The early tests examined the safety of the separation standards. As a result, in 1976 the separations were increased for Small or Light following aircraft. Then, the tests examined potential means to increase airport capacity or throughput. Examples include the Vortex Advisory System (VAS), the German Wake Vortex Warning System (WVWS), the French Systeme Anticipatif de Gestion des Espacements (SYAGE), and the NASA Aircraft Vortex Spacing System (AVOSS). Now, the tests are oriented toward studies of potential operational solutions, such as closer-spaced independent parallel runways, LDA approaches, and the Simultaneous Offset Instrument Approach (SOIA). The presentation will document what measurements were made in the many test programs and summarize the status of the raw and processed data. These datasets may be useful in new studies or as initial datasets for the development of new processing and analysis methods that will be used in future tests.

Hallock, J. N. and Eberle, W. R., editors

"AIRCRAFT WAKE VORTICES: A STATE-OF-THE-ART REVIEW OF THE UNITED STATES R&D PROGRAM"

FAA-RD-77-23, February 1977, DOT Transportation Systems Center, Cambridge, MA

The report summarizes the current state-of-the-art understanding of the aircraft wake vortex phenomenon and the results of the United States program to minimize the restrictions caused by aircraft wake vortices in the terminal environment. The vortex phenomenon, vortex avoidance systems, and vortex alleviation techniques are discussed.

Hallock, J. N. and Goldstone, L.

"US/UK VORTEX MONITORING PROGRAM AT HEATHROW AIRPORT"

Proceedings of 20th Symposium of Guidance and Control Panel, Plans and Developments for Air Traffic Systems, AGARD, 1975, pp. 24-1 to 24-9

Vortices shed from aircraft landing on Runway 28R at Heathrow Airport are being monitored in a joint US/UK program. Over 9100 vortex pairs have been recorded and analyzed and their motion correlated with the ambient meteorological conditions. It is shown that if the crosswind component measured near the runway threshold exceeds five knots, vortices linger near the extended runway centerline for a time more than one minute for less than 0.5 percent of the landings. This small percentage is almost entirely due to vortices from the heavy wide-body jets - the B-747, DC-10, and L-1011.

Hallock, J. N. and Holzaepfel, F.

"A REVIEW OF RECENT WAKE VORTEX RESEARCH FOR INCREASING AIRPORT CAPACITY"

Progress in Aerospace Sciences, Vol. 98, 2018, pp. 27-36.

This paper is a brief review of recent wake vortex research as it affects the operational problem of spacing aircraft to increase airport capacity and throughput. The paper addresses the questions of what do we know about wake vortices and what we do not know about wake vortices. The introduction of Heavy jets in the late 1960s stimulated the study of wake vortices for safety reasons and the use of pulsed lidars and the maturity of computational fluid dynamics in the last three decades have led to extensive data collection and analyses which are now resulting in the development and implementation of systems to safely decrease separations in the terminal environment. Although much has been learned about wake vortices and their behavior, there is still more to be learned about the phenomena of aircraft wake vortices.

Hallock, J. N. and Soares, M. A.

"COMPARISON OF TAKEOFF WAKE VORTICES OF HEAVY AND NON-HEAVY B-757"

DOT-VNTSC-FA27-PM-08-15, July 2008, Volpe Center, Cambridge, MA

In July 1996, a new wake vortex category was created for the B757-200 which placed it between revised Large and Heavy categories. Shortly thereafter, the B757-300, stretched version of the B757-200, was placed in service and soon was treated by Air Traffic Control as a Heavy aircraft due to its maximum certificated takeoff weight. Later, a Heavy version of the B757-200, the B757-200H, was also built. This is the third study examining the behavior of vortices from B757 aircraft; the first two examined landings and this study examines takeoffs. This study shows that the current Heavy versions of the B757 behave, from a wake vortex perspective, nearly identically to the non-Heavy version and all versions of the B757 can be treated the same on takeoff.

Hallock, J. N. and Soares, M. A.

"COMPARISON OF THE WAKE VORTICES OF HEAVY AND NON-HEAVY B757"

DOT/VNTSC-FAA-07-06, June 2007, DOT Volpe National Transportation Systems Center, Cambridge, MA

In July 1996, a new wake vortex category was created for the B757-200 which placed it between revised Large and Heavy categories. Shortly thereafter, the B757-300, stretched version of the B757-200, was placed in service and soon treated by Air Traffic Control as a Heavy aircraft due to its maximum certificated takeoff weight. This study examines the behavior of vortices from both aircraft during landing operations, and shows little difference between the vortices of the two B757 series. In fact, both measurements and theory indicate that B757-300 vortices decay somewhat faster than B757-200 vortices. Therefore, the B757-300 is being penalized by an unneeded increased wake vortex spacing during landing operations.

Hallock, J. N. and Soares, M. A.

"IS THE B757 REALLY A 'HEAVY' AIRCRAFT?"

AIAA Paper No. 2007-288, Reno, NV, January 200.

In July 1996, a new wake vortex category was created for the B757 which placed it between revised Large and Heavy categories. Shortly thereafter, the B757-300, stretched version of the B757-200, was placed in service and soon was treated by Air Traffic Control as a Heavy aircraft due to its maximum certificated takeoff weight. This study examines the behavior of vortices from both aircraft during approach/landing operations and shows little difference between the vortices of the two B757 series. In fact, both measurements and theory indicate that B757-300 vortices decay somewhat faster than B757-200 vortices. Therefore, the B757-300 is being penalized by unneeded increased wake vortex spacing during approach/landing operations.

Hallock, J. N. and Wang, F. Y.

"SUMMARY RESULTS FROM LONG-TERM WAKE TURBULENCE MEASUREMENTS AT SAN FRANCISCO INTERNATIONAL AIRPORT"

DOT-VNTSC-FA27-PM-04-13, July 2004, Volpe National Transportation Systems Center, Cambridge, MA

This report summarizes the results of an extensive wake turbulence data collection program at the San Francisco International Airport (SFO). Most of the landings at SFO are conducted on closely spaced parallel runways that are spaced 750 feet between centerlines (runways 28R and 28L). The purpose of the measurement program was to provide data to support the safety assessment of future enhancements to the Simultaneous Offset Instrument Approach procedure that permits continued use of both runways in deteriorating weather. The data collection was focused on wake behavior in the critical near-ground region where a wake encounter might be most hazardous. Limited measurements were also made at a glide slope altitude of about 530 feet to confirm prior results.

Hallock, J. N. and Winston, B. P.

"RUNWAY CONFIGURATION ANALYSIS FOR CHICAGO O'HARE AIRPORT USING VORTEX ADVISORY SYSTEM DATA"

FA186-PM-81-37, May 1981, DOT Transportation Systems Center, Cambridge, MA.

Based on an analysis of 14 months of data collected at O'Hare International Airport, it was found that decreased separations between runway threshold and outer marker would be permitted about 25 percent of the time. This figure assumes that the landing runways are selected as they are today without any input from the VAS. On the other hand, if the VAS were used to guide the decision on which runways should be used for landings, decreased separations would have been permitted about 40 percent of the time. This 15 percent increase would lead to large delay-dollar savings; \$150 to \$200

million in total IFR annual delay savings (1976 dollars) could be saved if VAS standards are applied instead of today's standards at the top 20 airports. The escalation of fuel prices certainly will increase these delay savings dollars.

Hallock, J. N. and Wood, W. D.

"STATUS OF THE WAKE VORTEX AVOIDANCE SYSTEM"

EASCON '74 Record, IEEE Electronics and Aerospace Systems Conference, 1974, pp. 250-256

The Federal Aviation Administration is pursuing a dual thrust program toward the solution of the wake vortex problem to be able to increase capacity to meet the air traffic density demands of the future while maintaining a high level of safety. One approach being investigated by NASA is to prevent the generation of a dangerous vortex via modification of the aircraft. The alternate approach, to be discussed herein and being undertaken by the Transportation Systems Center, is the design and development of a wake vortex avoidance system which will be used in the terminal airspace to detect and/or predict the presence of wake vortices, evaluate whether a threat of hazard exists, and command the hazard avoidance action. The status of the Wake Vortex Avoidance System is presented by briefly examining each of the modules making up a system: the predictive model and data base, vortex detecting and tracking subsystems, the hazard model, and the system concepts.

Hallock, J. N. and Wood, W. D.

"IMPACT OF WAKE TURBULENCE"

19th Annual Meeting and Technical Program, Air Traffic Control Association, Las Vegas, NV, October 1974

The paper presented the status of the Wake Vortex Avoidance System program by briefly reviewing what is known about vortices and the ability to predict their transport and demise; vortex detection and tracking sensors development; hazard definition; vortex data collection at Kennedy, Stapleton, and Heathrow International Airports; and various system concepts.

Hallock, J. N. and Wood, W. D.

"JOINT US/UK VORTEX TRACKING PROGRAM AT HEATHROW INTERNATIONAL AIRPORT, VOLUME I: EXECUTIVE SUMMARY"

FAA-RD-76-58.1, March 1976, DOT Transportation Systems Center, Cambridge, MA

From May 1974 through June 1975 the approach region to Runway 28R at Heathrow International Airport was equipped with aircraft wake vortex tracking equipment. The vortices from approximately 13000 aircraft were monitored along with the attendant meteorological conditions. The joint US/UK project represents a major step in learning how vortices move and die in the terminal environment. An overview of the Heathrow project is given and it is shown how the project has significantly contributed

to the capability to develop a vortex advisory system promising increased capacity through decreased aircraft separations.

Hallock, J. N., Burnham, D. C. and Sigona, J. J.

"ANALYSIS OF STALLED VORTICES AT DFW AIRPORT"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

Separation standards for final approach must account for the possibility that a wake vortex generated by a preceding aircraft may, because of interaction with the ground and the ambient crosswind, stall in the glide path. A ground-based array of anemometers was used extensively in the 1970s to detect stalled vortices. An array also gives measurements of the ambient wind close to the location where the vortices lateral motion is measured. Data recently collected at Dallas-Ft. Worth Airport are analyzed and compared to the 1970s results. The analysis concentrates on the arrivals when atmospheric turbulence was low to optimize the vortex detection and to select conditions when long vortex lifetimes can be expected.

Hallock, J. N., Burnham, D. C. and Wang, F. Y.

"AN INVENTORY OF VOLPE CENTER WAKE MEASUREMENTS"

DOT-VNTSC-FA27-PM-07-12, Oct. 2007, Volpe National Transportation Systems Center, Cambridge, MA.

The Volpe Center became involved with the subject of aircraft wake turbulence in late 1970, soon after the Center was established. The first test site was set up at the John F. Kennedy International Airport (JFK) in early 1971. Since that time many test programs have been initiated to collect wake vortex behavior. This report provides an overview of the state of the data from that first test site on runway 31R at JFK to October 2007. It includes just the test programs (or portions thereof) for which the Volpe Center was responsible.

Hallock, J. N., Burnham, D. C., Jenkins, J., Konopka, J. and Rudolph, R.

"WAKE VORTEX TRACKING USING FRANKFURT WINDLINE"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

The space between the Frankfurt parallel runways (518 m apart) is instrumented with 10 sonic anemometers (25-Hz measurement rate), which are used to measure the ambient crosswind. One-second averaged data have been processed to track the motion and strength of wake vortices travelling

between the two runways. Future work will (a) determine vortex location in real time and (b) study turbulence levels inside wake vortices using 25-Hz data.

Hallock, J. N., Burnham, D. C., Tombach, I. H., Brashears, M. R., Zalay, A. D. and Barber, M. R.

"GROUND-BASED MEASUREMENTS OF THE WAKE VORTEX CHARACTERISTICS OF A B747 AIRCRAFT IN VARIOUS CONFIGURATIONS"

AIAA Paper No. 1977-0009, Los Angeles, CA, January 1977

A Boeing 747 aircraft flew 54 passes at low level over ground-based sensors. Vortex velocities were measured by a laser-Doppler velocimeter, an array of monostatic acoustic sounders, and an array of propeller anemometers. Flow visualization of the wake was achieved using smoke and balloon tracers. Preliminary results were obtained on the initial downwash field, the time for merging of the multiple vortices, the velocity fields, vortex decay, and the effects of spoilers and differential flap settings on the dissipation and structure of vortices.

Hallock, J. N., editor

"PROCEEDINGS OF THE AIRCRAFT WAKE VORTICES CONFERENCE"

FAA-RD-77-68, June 1977, DOT Transportation Systems Center, Cambridge, MA

This volume contains the proceedings of a conference on aircraft wake vortices held at the DOT Transportation Systems Center on March 15-17, 1977. The contributed papers discuss technological advances in the knowledge of the phenomenon, its effects on aircraft, alleviation techniques, and vortex avoidance systems designed to permit decreases in delays at major airports.

Hallock, J. N., editor

"PROCEEDINGS OF THE AIRCRAFT WAKE VORTICES CONFERENCE"

DOT/FAA/SD-92/1.1 and 1.2 (Volumes 1 and 2), June 1992, DOT Volpe National Transportation Systems Center, Cambridge, MA.

These volumes contain the proceedings of the international conference of Aircraft Wake Vortices held at the Quality Hotel Capitol Hill, Washington, DC, on October 29-31, 1991. The contributed papers discuss technological advances in the knowledge of the phenomenon, its effect on aircraft and airport capacity, detection techniques, and vortex avoidance schemes.

Hallock, J. N., Goldstone, L., Nevill, R. G. and Cooper, D. C.

"MONITORING OF AIRCRAFT WAKE VORTICES AT HEATHROW AIRPORT"

Proceedings Int. Conf. on Future of Aircraft All-Weather Operations, Inst. Electrical Engineers, London, November 1976, pp. 38-41

Aircraft separation to avert entrainment in wake vortices is weighed against loss of traffic capacity at airports, and meteorological conditions unfavorable to the formation of wake vortices and their attendant hazards are examined; the organization of vortex data collection sites is discussed. Experience with vortex data collection sites at London, New York, and Denver is surveyed. Anemometer baselines and an acoustic Doppler system are described. Delineation of safety zones and determination of the rate at which shed vortices leave the safety zone are discussed.

Hallock, J. N., Greene, G. C. and Burnham, D. C.

"WAKE VORTEX RESEARCH -- A RETROSPECTIVE LOOK"

Air Traffic Control Quarterly, Vol. 6, No. 3, September 1998, pp. 161-178

During the 1970's and the early 1980's, the FAA and NASA conducted extensive wake vortex research programs with the goal of safely increasing airport capacity. The FAA program focused on developing an extensive data base, the technology for predicting and/or detecting the presence of a vortex, and advising controllers when aircraft separations could be safely reduced. The NASA program emphasized reducing the wake hazard through changes to the aerodynamic characteristics of the aircraft. Both programs made significant technical progress, even though neither program resulted in an implementable solution. Research in the 1990's has the same goal and many of the same challenges as the earlier research. However, now both the FAA and NASA programs are focused on wake detection/avoidance. The primary difference between the FAA and NASA programs is the time scale, with the NASA program emphasizing technology for a future automated ATC system and the FAA program emphasizing enhancements to today's system. This paper discusses the most important lessons learned from prior research by both the FAA and NASA, and in particular, how prior research has shaped the issues, requirements, and constraints which will affect any proposed solution.

Hallock, J. N., Greene, G. C., Tittsworth, J. A., Strande, P. D. and Wang, F. Y.

"USE OF SIMPLE MODELS TO DETERMINE WAKE VORTEX CATEGORIES FOR NEW AIRCRAFT"

AIAA Paper 2015-3172, June 2015, Dallas, TX.

The paper describes how to use simple models and, if needed, sensitivity analyses to determine the wake vortex categories for new aircraft. The methodology provides a tool for the regulators to assess the relative risk of introducing new aircraft into the current fleet.

Hallock, J. N., Osgood, S. P. and Konopka, J.

"WAKE VORTEX EFFECTS ON PARALLEL RUNWAY OPERATIONS"

AIAA Paper No. 2003-0379, Reno, NV, January 2003

Aircraft wake vortex behavior in ground effect between two parallel runways at Frankfurt/Main International Airport was studied. The distance and time of vortex demise were examined as a function of crosswind, aircraft type, and a measure of turbulence. Vortex decay in ground effect is little influenced by ambient turbulence and is seen to be a stochastic process.

Hallock, J. N., Sigona, J. J. and Burnham, D. C.

"MEASUREMENTS OF VORTICES STALLED NEAR EXTENDED RUNWAY CENTERLINE ON FINAL APPROACH"

AIAA Paper No. 1998-0591, Reno, NV, January 1998.

Longitudinal separation standards for final approach must account for the possibility that a wake vortex generated by the preceding aircraft may, because of interaction with the ground and the ambient crosswind, remain stalled in the glide path. A ground-based array of anemometers was used extensively in the 1970s to detect such stalled vortices. Recent developments in the capabilities of such arrays have permitted completely automatic operation and estimates of vortex height and circulation. The array also gives measurements of the ambient wind close to the location where the vortex lateral motion is measured. Data collected over 10 months in 1994-95 at Kennedy Airport are analyzed and compared to the 1970s results and to a mathematical model for the probability of encountering a wake vortex in the absence of vortex decay. The analysis concentrates on the arrivals when atmospheric turbulence was low (1) to optimize the vortex detection sensitivity of the array and (2) to select conditions where long vortex lifetimes can be expected.

Hallock, J. N., Soares, M. A. and Chen, S. S.

"COMPARISON OF THE WAKE VORTICES OF HEAVY AND NON-HEAVY B-757 ON APPROACH"

DOT-VNTSC-FA27-PM-08-14, June 2008, Volpe Center, Cambridge, MA

In July 1996, a new wake vortex category was created for the B757-200 which placed it between revised Large and Heavy categories. Shortly thereafter, the B757-300, stretched version of the B757-200, was placed in service and soon was treated by Air Traffic Control as a Heavy aircraft due to its maximum certificated takeoff weight. Later, a Heavy version of the B757-200, the B757-200H, was also built. This is the second study examining the behavior of vortices from B757 aircraft during landing operations, and shows little difference between the Heavy and non-Heavy vortices of the B757. Both measurements and theory indicate that the Heavy B757 vortices decay somewhat faster than B757-200 vortices. Therefore, the current Heavy B757 is being penalized by an unneeded increased wake vortex spacing during landing operations.

Hallock, J. N., Spitzer, E. A. and Wood, W. D.

"VORTEX ADVISORY SYSTEM"

Patent 4,137,764, February 1979, DOT Transportation Systems Center, Cambridge, MA

The invention relates to determining the appropriate spacing between fixed-wing aircraft arriving at runways so as to permit the minimum separation commensurate with safe operation as a function of the atmospheric conditions. More specifically, this invention is directed to a vortex advisory system which will enable flight controllers to vary the separation between aircraft as a function of the accurately predicted motion of wake vortices produced by the aircraft.

Hallock, J. N., Tung, C. and Sampath, S.

"CAPACITY AND WAKE VORTICES"

ICAS-2002-7.9.1, Toronto, Canada, September 2002

Vortex separation standards preclude hazardous encounters, but are oftentimes very conservative. A key to increasing airport capacity is to know when vortices are not a hazard so that aircraft can land and take off with closer intervals. This paper provides an overview of the highlights of a conference held in London to address the capacity and wake vortices issue.

Hallock, J. N., Wang, F. Y. and Greene, G. C.

"WAKE VORTEX MEASUREMENTS TO SUPPORT SAFETY ASSESSMENT OF THE SIMULTANEOUS OFFSET INSTRUMENT APPROACH PROCEDURE AT SFO"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

This paper summarizes the results of an extensive wake turbulence data collection program at the San Francisco International Airport (SFO). Most of the landings at SFO are conducted on closely spaced parallel runways that are spaced 750 feet between centerlines (runways 28R and 28L). The purpose of the measurement program was to provide data to support the safety assessment of the Simultaneous Offset Instrument Approach (SOIA) procedure that permits continued use of both runways in deteriorating weather. The data collection was focused on wake behavior in the near-ground region where a wake encounter might be most hazardous. Limited measurements were also made at a glide slope altitude of about 160 meters (530 feet). The specific objective was to more accurately measure wake vortex behavior to refine FAA flight procedure development and analysis tools. These tools will be used to develop safety and procedural requirements for closely spaced parallel runway operations. Wake turbulence data were collected for over 260,000 landing aircraft near the thresholds of Runways 28L and 28R where the glide slope height is approximately 20 meters (65 feet). The wake turbulence data were taken over all seasons and all-weather conditions, 24 hours per day, 7 days per week. The SOIA procedure, as currently designed for SFO, will be used when the cross-runway component of the total wind is 10 knots or less. 'SOIA conditions' at SFO typically occur in the morning or late evening and are often characterized by a fog or marine layer with low cloud ceilings and light surface winds. Stronger winds typically occur in the afternoon after the fog or marine layer has burned off and visibility and cloud ceiling conditions would support visual approach operations. Accordingly, the wake

data were analyzed and categorized relative to the cross-runway component of the total wind, as measured by the Automated Surface Observing System (ASOS), to better correlate wake transport and decay times to conditions when SOIA operations would be conducted. The vortex wake data support the conclusion that when the stagger between aircraft on adjacent approach courses is relatively small (approximately 1 nm for an approach speed of 130 kts), it is not possible for the wake from one aircraft to be blown by the wind into the path of the other aircraft quickly enough to create a hazard. The data are consistent with typical observed aircraft pairings during current SFO visual approach operations as well as proposed SOIA operations.

Hallock, J. N., Whitney, J. E. and Burnham, D.C.

"WIND CRITERIA TO RELIEVE WAKE VORTEX EFFECTS ON DEPARTURE"

AIAA Paper No. 1999-3420, Norfolk, VA, June 1999

Aircraft wake vortices from departing aircraft represent one impediment on the throughput of an airport. To preclude a hazardous wake encounter, separation standards are employed to separate aircraft so that the vortices from a lead aircraft can translate away or decay sufficiently to permit a following aircraft to safely traverse the same airspace of the lead aircraft. Wind is a primary influence on vortex behavior. This study examined the behavior of the wake vortices of over 16,000 takeoffs at O'Hare International Airport to determine if wind criteria could be used to permit closer spacings on departure. Both a crosswind and a total wind criterion were developed.

Hallock, J. N., Winston, B. P., Burnham, D. C., Sullivan, T. E. and McWilliams, I. G.

"JOINT US/UK VORTEX TRACKING PROGRAM AT HEATHROW INTERNATIONAL AIRPORT, VOLUME II: DATA ANALYSIS"

FAA-RD-76-58,II, November 1977, DOT Transportation Systems Center, Cambridge, M.

From May 1974 through June 1975, the approach region to runway 28R at Heathrow International Airport was equipped with aircraft wake vortex tracking equipment. The vortices from approximately 13,000 aircraft were monitored along with the attendant meteorological conditions. The joint US/UK project represents a major step in learning how vortices move and die in the terminal environment. Volume II describes the entire project from the workings and locations of the equipment to the analysis of the data.

Hallock, J. N., Winston, B. P., Sullivan, T. E. and Burnham, D. C.

"TSC WAKE VORTEX DATA BASE AND APPLICATIONS"

Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, DOT Transportation Systems Center, June 1977, pp. 67-80.

An extensive data base is being compiled on the motion and decay of wake vortices near the ground. To date, data for over 40,000 vortex pairs have been recorded, analyzed, and entered into the data base. The rationale for the data collection program at each site is presented along with a description of the entries into the data base and the results of some preliminary studies using the data base.

Hallock, J. N., Wood, W. D. and Spitzer, E. A.

"THE MOTION OF WAKE VORTICES IN THE TERMINAL ENVIRONMENT"

Proceedings of the Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorology Society, 1974, pp. 393-398

A Wake Vortex Avoidance System (WVAS) is being designed and developed for use in the terminal airspace to detect and/or predict the presence of vortices, to evaluate the threat, and to command the hazard avoidance action. The WVAS will consist of a predictive model and data base, a vortex detection and tracking subsystem, a hazard model, and a data processing and display subsystem. The paper describes the vortex detection and tracking systems (a pulsed acoustic, a Doppler acoustic, a ground wind, and a laser Doppler system), the JFK Vortex Test Site and its extensive meteorological network, and several WVAS concepts ranging from a very simple meteorological system to a complex and fully-automated system.

Hallock, J. N., Wood, W. D. and Spitzer, E. A.

"PREDICTIVE TECHNIQUES FOR WAKE VORTEX AVOIDANCE"

Proceedings of 20th Symposium of Guidance and Control Panel, Plans and Developments for Air Traffic Systems, AGARD, 1975, pp. 23-1 to 23-11

Aircraft wake vortices represent a major impediment to increasing runway capacity. Separation criteria are conservative most of the time and thus traffic is unnecessarily delayed by always adhering to the present inflexible regulations. Systems which employ vortex tracking sensors and/or meteorological sensors to determine safe reduced spacings are being designed. Any wake vortex avoidance strategy relies upon the ability to predict vortex transport and decay. The paper discusses vortex behavior, preliminary predictive models based upon the tracking of vortices from over 24,000 landing aircraft and systems and their implementation to provide the capability of using adaptive separations.

Hallock, J. N., Wood, W. D. and Spitzer, E. A.

"THE WAKE VORTEX ADVISORY SYSTEM"

Proceedings Int. Conf. on Electronic Navigational Aid Systems for Aircraft, Federation des Industries Electriques et Electroniques, November 1977, Paris, France, pp. 269-273

The vortices from over 50,000 landing aircraft have been monitored at Kennedy, Stapleton, O'Hare, and Heathrow International Airports. Using this data base, a wind criterion has been defined which can be used as a vortex condition indicator; by measuring the wind velocity in the runway approach zone and comparing the velocity with the wind criterion, the times when the aircraft spacing may be reduced safely to three nautical miles for all aircraft are delineated. A Vortex Advisory System has been implemented at the Chicago O'Hare International Airport and will be fully operational in December 1977.

Halpert, J. F., Prescott, D. H., Yechout, T. R. and Arndt, M.

"AERODYNAMIC OPTIMIZATION AND EVALUATION OF KC-135R WINGLETS, RAKED WINGTIPS, AND A WINGSPAN EXTENSION"

AIAA Paper 2010-0057, January 2010, Orlando, FL.

The ability of winglets and raked wingtips to reduce the drag of an aircraft are fairly well known. In 2008, the Air Force Research Laboratory and Air Mobility Command tasked the US Air Force Academy to examine the effect that winglets would have on the KC-135 Stratotanker. This investigation focused on finding an optimized configuration for the winglets. Wind tunnel tests were run on a range of Mach numbers (0.2, 0.3, 0.4), winglet sizes, cant angles (5-25 deg), and toe out angles (0-8 deg). An optimized winglet was found, but further testing with raked wingtips and a wingspan extension configuration were found to offer similar aerodynamic performance. While the optimal winglet offered increases in endurance and range potential of 5.62 and 3.55 percent respectively, a raked wingtip with 20 deg of additional leading-edge sweep offered increases of 8.32 and 4.69 percent. Meanwhile, the wingspan extension offered increases of 7.02 and 4.21 percent. Depending on the wingtip modification implemented and actual mission analysis evaluated, the KC-135 could see increases in range from 6-12 percent and increases in endurance from 6-13 percent. With set missions, the different wingtip modifications could decrease fuel burn by up to 8 percent. In addition, the stability analysis found that the static stability changes on the aircraft are very small.

Halsey, N. G. J.

"THE PREDICTION OF VERY SHORT PERIOD CROSSWIND SPEED USING STATISTICAL TECHNIQUES"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

Any future wake vortex advisory system needs to have the capability to predict the strength of the crosswinds affecting aircraft in the vicinity of the runway. Wind measurements are routinely taken at all airports and these measurements are available to the pilot through air traffic control. This is problematic since it is unlikely that the measured wind speed would be appropriate to the precise time and location of the aircraft on either final approach or after take-off. It is known that the use of persistence gives a reasonable forecast of wind speed over short time periods or short distances although the use of predictive statistical techniques can reduce forecast errors quite markedly. This

paper describes the use of various techniques for crosswind prediction as applied to a large sample of one-minute readings taken at Memphis airport during 1995. Results are presented showing the improvements in forecast accuracy that can be gained using these techniques.

Halsey, N. G. J.

"THE PREDICTION OF CROSSWIND COMPONENTS OVER VERY SHORT PERIODS IN THE CONTEXT OF WAKE VORTEX AVOIDANCE"

Technical Report No. 244, May 1998, Meteorological Office, Berkshire, UK

This paper describes attempts to predict one-minute mean crosswind components over short periods of at most twenty minutes. This work has been carried out in the context of research into the prediction and avoidance of aircraft wake vortices. It is known that the use of persistence (assuming that the wind speed will remain constant from one minute to the next) gives a useful forecasting technique over such short periods. However, it has been demonstrated that the level of accuracy from such forecasts is only marginally useful when attempting to predict the motion and decay of aircraft wake vortices. The prediction techniques used are purely statistical in nature although some meteorological knowledge is applied to some of the outcomes, i.e., results are not applied unless they are sensible in a meteorological context. The main method used is that of an autoregressive, integrated, moving average (ARIMA) process of which several alternatives are suggested and compared. The results of the study show that a straightforward ARIMA process can reduce the standard error of a prediction using persistence by around 15% with the possibility of future enhancements increasing this figure to 25%.

Ham, N. D.

"SOME CONCLUSIONS FROM AN INVESTIGATION OF BLADE-VORTEX INTERACTION"

Journal of American Helicopter Society, Vol. 10, No. 2, pp. 1-5.

Selected experimental spanwise airload harmonics are presented for single and rear tandem rotor configurations for various rotor shaft angles, advance ratios, and thrust loadings.

Hama, F. R.

"PROGRESSIVE DEFORMATION OF A CURVED VORTEX FILAMENT BY ITS OWN INDUCTION"

Phys. Fluids, Vol. 5, No. 10, October 1962, pp. 1156-1162

Progressive three-dimensional deformation of an initially parabolic, plane curved vortex due to its own induction is numerically obtained in this paper using the localized-induction concept instead of through the full Biot-Savart law. It is shown that, after the region near the vortex rises up from the plane of the initial orientation, a helical deformation takes place on the legs of the parabola. The helix, which rotates in the direction opposite to the circulatory rotation around the vortex filament, is found

to travel away toward the far ends of the parabola as the vortex keeps rising, while increasing the amplitude and extent of the helical deformation. Similar computations also carried out with a hyperbolic initial shape resulted in essentially the same conclusions as the parabola but with much better numerical stability, as well as with an exponential initial configuration, which grew into somewhat more complicated patterns, yet maintained the essential feature of the helical deformation.

Hamilton, D. W. and Proctor, F. H.

"WAKE VORTEX TRANSPORT IN PROXIMITY TO THE GROUND"

19th Digital Avionics Systems Conference, Philadelphia, PA, October 2000

A sensitivity study for aircraft wake vortex transport has been conducted using a validated large eddy simulation model. The study assumes neutrally stratified and nonturbulent environments and includes the consequences of the ground. The numerical results show that the nondimensional lateral transport is primarily influenced by the magnitude of the ambient crosswind and is insensitive to aircraft type. In most of the simulations, the ground effect extends the lateral position of the downwind vortex about one initial vortex spacing in the downstream direction. Further extension by as much as one vortex spacing occurs when the downwind vortex remains 'in ground effect' for relatively long periods of time. Results also show that a layer-averaged ambient wind velocity can be used to bound the time for lateral transport of wake vortices to insure safe operations on a parallel runway.

Hammarlund, H., Hillgren, R. and Karlsson, F.

"REDUCTION OF WAKE VORTEX TRANSIENTS IN THE JAS 39 GRIPEN"

AIAA Paper 2007-6765, August 2007, Hilton Head, SC.

JAS 39 Gripen is a modern aerodynamically unstable multi role combat fighter. It has delta canard configuration with all moving canards. It has very high demands on agility, precision, flying qualities and carefree maneuvering. For high precision and performance during demanding control tasks a blend of pure angle of attack vane signal and a complementary filtered angle of attack was selected for feedback at a cost of some sensitivity for wake vortex transients at high load factor and high angle of attack. The very robust carefree maneuver limit function enables the pilot to sustain max commands and thus expose the aircraft to wake vortex passages and their transients. After several wake vortex related incidents in the Swedish Air Force service a flight control system control law change was necessary. A wake vortex model was developed and validated with available flight test data from earlier wake vortex passages. The wake vortex model was then used to find the actual problem areas in terms of flight conditions, load factor and angle of attack at the wake vortex passage. The flight control system change was implemented and flight tested. The flight control laws update is implemented in the JAS 39 Gripen Flight Control System and it will significantly reduce the risk for wake vortex related incidents.

Hammer, J.

"SAFETY ANALYSIS OF AN APPROACH SPACING FOR INSTRUMENT APPROACHES (ASIA) APPLICATION USING ADS-B"

Air Traffic Control Quarterly, Vol. 11, No. 3, 2003, pp. 203-224.

This paper illustrates new techniques being adopted by some members of industry for analysis of the safety of aircraft surveillance applications. The techniques are illustrated using the example flight deck application of Approach Spacing for Instrument Approaches (ASIA). The techniques include analysis of the operational procedures, conducting a hazard analysis, and treating identified hazards in a fault-tree analysis. The fault-tree analysis in turn results in system requirements on various subsystems that support the operational application. The specific analysis of the approach spacing application results in a requirement that the probability of presenting hazardously misleading information be held to less than 0.00001 per operation. The 0.00001 value represents 'major' system criticality, and is a criticality that is considered by avionics vendors to be achievable within reasonable cost constraints. If the benefits of reduced spacing that are offered by the approach spacing concept are significant enough to justify the cost, users may find that it is worthwhile to equip their aircraft with such a capability.

Hammer, J.

"CASE STUDY OF PAIRED APPROACH PROCEDURE TO CLOSELY SPACED PARALLEL RUNWAYS"

Air Traffic Control Quarterly, Vol. 8, No. 3, 2000, pp. 223-252

This paper analyzes a new procedure called paired approach which has been proposed for use with very closely spaced parallel runways (less than 2500 ft. between runway centerlines). The intent of the procedure is to make better use of runways during instrument meteorological conditions. The analysis includes consideration of wake turbulence and collision avoidance. We find that for very closely spaced parallel runways, an angled, offset approach is necessary to simultaneously avoid wake turbulence and collision risk.

Han, C. and Cho, J.

"UNSTEADY TRAILING VORTEX EVOLUTION BEHIND A WING IN GROUND EFFECT"

Journal of Aircraft, Vol. 42, No. 2, March-April 2005, pp. 429-434

The unsteady evolution of trailing vortex sheets in ground effect is simulated by the use of a discrete vortex method. The ground effect is included by image method. Two cases of unsteady vortex evolution behind lifting lines (an elliptic loading and a fuselage/flap-wing configuration) are simulated for several ground heights. The present method is validated by comparison of the simulated wake roll-up shapes to published numerical results. For a lifting line with an elliptic loading, the ground has the effect of moving the wingtip vortices laterally outward and suppressing the development of the vortex. An increase in the wing loading has the effect of moving the wingtip vortex more laterally outward. The rotation of the wake vortices behind a fuselage/part-span flap configuration in ground effect is less than the case of flight out of the ground effect.

Han, C. and Mason, W. H.

"INVISCID WING-TIP VORTEX BEHAVIOR BEHIND WINGS IN CLOSE FORMATION FLIGHT"

Journal of Aircraft, Vol. 42, No. 3, May-June 2005, pp. 787-788

This study demonstrates the inviscid near-wake behavior behind aircraft flying in close formation. The prediction of the wake behavior shows that the distance between the wings has the effect of moving the wake vortices up behind wing tips facing each other. The relative heights between aircraft cause a large asymmetric evolution of wake vortices, which will result in a change of aerodynamic characteristics. Although the present results are obtained based on potential flow theory, it can be concluded that the prediction of the wake roll-up behavior behind aircraft in formation flight might be of considerable importance in the prediction of the aerodynamic performance.

Han, C., Cho, L. and Cho, J.

"WAKE SHAPES BEHIND WINGS IN CLOSE FORMATION FLIGHT NEAR THE GROUND"

Journal of Mechanical Science and Technology, Vol. 19, No. 2, 2005, pp. 674-681.

The unsteady evolution of trailing vortex sheets behind wings in close formation flight near the ground is simulated using a discrete vortex method. The ground effect is included by an image method. The method is validated by comparing computed results with other numerical results. For a lifting line with an elliptic loading, the ground has an effect of moving wingtip vortices laterally outward and suppressing the development of vortex evolution. The gap between wings in close formation flight has an effect of moving up wingtip vortices facing each other. For wings flying in parallel, the ground effect causes the wingtip vortices facing each other to move up, and it makes the opposite wing tip vortices to move laterally outward. When there is a relative height between the wings in ground effect, right-hand side wingtip vortices from a mothership move laterally outward.

Han, J.

"LARGE EDDY SIMULATIONS OF AIRCRAFT WAKE VORTICES IN A HOMOGENEOUS ATMOSPHERIC TURBULENCE (CROW INSTABILITY, VORTEX LIFESPAN)"

Ph.D. Thesis, 1998, North Carolina State University, Raleigh, NC.

This dissertation is composed of two separate papers where atmospheric turbulence effects on the behavior of aircraft wake vortices are studied using a validated large eddy simulation model. Information from this study may contribute to the development of a predictor algorithm for the National Aeronautics and Space Administration's (NASA) Aircraft Vortex Spacing System (AVOSS), which will determine safe operating spacing between arriving and departing aircraft and provide a safe reduction in separation of aircraft compared to the now-existing flight rules. In the first paper, the development of Crow instability in a homogeneous field of turbulence is studied. The Crow instability

becomes well developed in most atmospheric turbulence levels, but in strong turbulence the vortex pair deforms more irregularly due to turbulence advection. The maximum Crow instability wavelength decreases with increasing nondimensional turbulence intensity (ti) while it increases with increasing turbulence integral length scale. The vortex lifespan is controlled primarily by ti and decreases with increasing ti , while the effect of integral scale of turbulence on vortex lifespan is of minor importance. The lifespan of vortex in our numerical simulations is estimated to be about 40% larger than the theoretically predicted value. This larger lifespan compared with an analytic theory agrees very well with the data from laboratory experiments and is caused by slower growth in the middle of the vortex lifespan. The maximum deviation in lifespan from the average value due to ambient turbulence alone is about 7% of the mean for small ti and about 20% of the mean for large ti , showing much less scatter in lifespan compared with atmospheric observations. In the second paper, the vortex decay and descent in a homogeneous field of turbulence is investigated. The decay rate of the vortex circulation increases clearly with increasing ambient turbulence level but decreases with increasing radial distance, which is consistent with field observations. Simple vortex decay models are proposed as functions of ti and radial distance. A Gaussian type of vortex decay model can be applied at larger radial distances, while an exponential type of vortex decay model can be applied at smaller radial distances near the core, but the latter can be extended up to a radial distance of about half of the initial vortex separation distance for strong turbulence. The circulation averaged over radial distance, which is related to the rolling moment of an encountering aircraft, shows a Gaussian decay for weak and moderate turbulence and an exponential decay for strong turbulence. A model for the vortex descent based on the vortex decay model is also proposed as a function of ti and dimensionless time.

Han, J., Lin, Y.-L., Arya, S. P. and Kao, C.-T.

"LARGE EDDY SIMULATION OF AIRCRAFT WAKE VORTICES: ATMOSPHERIC TURBULENCE EFFECTS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 131-144

Ambient atmospheric turbulence effects on aircraft wake vortices have been studied using a validated large eddy simulation model. The results show that the Crow instability becomes well developed in most atmospheric turbulence levels, but in strong turbulence the vortex pair deforms more irregularly due to turbulence advection. Strong ambient turbulence tends to accelerate the instability growth, while the maximum instability wavelength tends to decrease with increasing dimensionless turbulence intensity. Compared with two-dimensional simulation results, a decrease in circulation with time is significantly enhanced by three-dimensional ambient turbulence.

Han, J., Lin, Y.-L., Arya, S. P. and Proctor, F. H.

"NUMERICAL STUDY OF WAKE VORTEX DECAY AND DESCENT IN HOMOGENEOUS ATMOSPHERIC TURBULENCE"

AIAA Journal, Vol. 38, No. 4, April 2000, pp. 643-656.

Numerical simulations are performed to isolate the effect of ambient turbulence on the wake vortex decay rate within a neutrally stratified atmosphere. Simulations are conducted for a range of turbulence intensities by injecting wake vortex pairs into an approximately homogeneous and isotropic turbulence field. Consistent with field observations, the decay rate of the vortex circulation increases clearly with increasing levels of ambient turbulence. Based on the results from the numerical simulations, simple decay models for the vortex pair are proposed as functions of nondimensional ambient turbulent intensity, nondimensional radial distance, and nondimensional time. For strong atmospheric turbulence, the model predictions are in reasonable agreement with the observational data. For weak turbulence with stable stratification, the model, based on turbulence dissipation alone, underestimates circulation decay with consistent overestimation of vortex descent, unless stratification effects are included.

Han, J., Lin, Y.-L., Arya, S. P. and Proctor, F. H.

"LARGE EDDY SIMULATION OF AIRCRAFT WAKE VORTICES IN A HOMOGENEOUS ATMOSPHERIC TURBULENCE: VORTEX DECAY AND DESCENT"

AIAA Paper No. 1999-0756, Reno, NV, January 1999

The effects of ambient turbulence on decay and descent of aircraft wake vortices are studied using a validated, three-dimensional, large-eddy simulation model. Numerical simulations are performed to isolate the effect of ambient turbulence on wake vortex decay rate within a neutrally-stratified atmosphere. Simulations are conducted for a range of turbulence intensities, by injecting wake vortex pairs into an approximately homogeneous and isotropic turbulence field. The decay rate of the vortex circulation increases clearly with increasing ambient turbulence level, which is consistent with field observations.

Han, J., Lin, Y.-L., Schowalter, D. G. and Arya, S. P.

"LARGE EDDY SIMULATION OF AIRCRAFT WAKE VORTICES WITHIN HOMOGENEOUS TURBULENCE: CROW INSTABILITY"

AIAA Journal, Vol. 38, No. 2, February 2000, pp. 292-300

Ambient atmospheric turbulence effects on aircraft wake vortices are studied using a validated large eddy simulation model. Our results confirm that the most amplified wavelength of the Crow instability and the lifetime of wake vortices are significantly influenced by ambient turbulence. The Crow instability becomes well developed in most atmospheric turbulence levels, but in strong turbulence the vortex pair deforms more irregularly due to turbulence advection. The most amplified wavelength of the instability decreases with increasing dimensionless turbulence intensity n , although it increases with increasing turbulence integral length scale. The vortex lifespan is controlled primarily by n and decreases with increasing n , whereas the effect of integral scale of turbulence on vortex lifespan is of minor importance. The lifespan is estimated to be about 40% larger than Crow and Bate's predicted value but in agreement with Sarpkaya's recent modification to Crow and Bate's theory. This larger

lifespan is also supported by data from water tank experiments and direct numerical simulations. There appears to be a possibility that the scatter in vortex lifespans due to ambient turbulence alone decreases with increasing Reynolds number, whereas larger scatter of lifespans in flight tests may result from other factors such as stratification, wind shear, and inhomogeneous ambient turbulence.

Han, J., Lin, Y.-L., Schowalter, D. G., Arya, S. P. and Proctor, F. H.

"LARGE EDDY SIMULATIONS OF AIRCRAFT WAKE VORTICES: ATMOSPHERIC TURBULENCE EFFECTS"

12th Symposium on Boundary Layers and Turbulence, 1997, pp. 237-238

Large eddy simulations (LES) of a vortex pair induced by aircraft with a homogeneous atmospheric turbulence are performed. Vortex decay and deformation, onset, and development of mutual induction sinusoidal instability (Crow instability), and vortex bursting are investigated as functions of turbulence parameters.

Han, J., Lin, Y.-L., Schowalter, D. G., Arya, S. P. and Proctor, F. H.

"LARGE EDDY SIMULATION OF AIRCRAFT WAKE VORTICES WITHIN HOMOGENOUS TURBULENCE: CROW INSTABILITY"

AIAA Journal, Vol. 38, No. 2, February 2000, pp. 292-300.

Ambient atmospheric turbulence effects on aircraft wake vortices are studied using a validated large eddy simulation model. Our results confirm that the most amplified wavelength of the Crow instability and the lifetime of wake vortices are significantly influenced by ambient turbulence. The Crow instability becomes well developed in most atmospheric turbulence levels, but in strong turbulence the vortex pair deforms more irregularly due to turbulence advection. The most amplified wavelength of the instability decreases with increasing dimensionless turbulence intensity n , although it increases with increasing turbulence integral length scale. The vortex lifespan is controlled primarily by n and decreases with increasing n , whereas the effect of integral scale of turbulence on vortex lifespan is of minor importance. The lifespan is estimated to be about 40% larger than Crow and Bate's predicted value but in agreement with Sarpayka's recent modification to Crow and Bate's theory. This larger lifespan is also supported by data from water tank experiments and direct numerical simulations. There appears to be a possibility that the scatter in vortex lifespans due to ambient turbulence alone decreases with increasing Reynolds number, whereas larger scatter of lifespans in flight tests may result from other factors such as stratification, wind shear, and inhomogeneous ambient turbulence.

Han, Y. O.

"DIFFUSED TIP VORTEX STRUCTURE GENERATED BY A SLOTTED TIP ROTOR BLADE"

AIAA Paper No. 2005-0057, Reno, NV, January 2005

An experiment was conducted to understand the flow field surrounding a slotted helicopter rotor blade that directs a part of its incident flow along the spanwise direction. Flow visualization and 3-component LDV measurements were made on tip vortices trailing from the slotted blade for four different slot configurations to quantify the swirl and axial velocity components, mean kinetic energy, core development and its turbulent properties at a fixed wake age of 145 degrees. The presence of the slots created a flow velocity in the spanwise direction that resulted in much diffused vortex structure at very early wake ages. An increase in number of slots was shown to increase the diffusion of the tip vortices. However, the slot optimization study indicated that the slotted blade with two slots showed sufficient vortex diffusion, and as much as the blade with four slots. The axial velocity of tip vortices generated by the slotted blade was found to increase with more slots, which is different to the baseline case. Also, the convection swirl of the slipstream about the hub axis was found to be higher for the slotted blade case. This results in an increased mean kinetic energy of the tip vortices explaining the increased power requirement of the slotted blade rotor.

Han, Y. O. and Leishman, J. G.

"INVESTIGATION OF HELICOPTER ROTOR-BLADE-TIP-VORTEX ALLEVIATION USING A SLOTTED TIP"

AIAA Journal, Vol. 42, No. 3, March 2004, pp. 524-535

A slotted tip was developed to modify the characteristics of the strong vortex trailed from the tip of a small-scale helicopter blade. Forward-facing slots directed a slight amount of the incident flow in the spanwise direction, which was vented at the side edge of the blade tip. This caused the tip vortex to detach from the blade tip face, and introduced turbulent vortlets into the laminar core of the developing vortex. The resulting wake flow field was investigated using flow visualization and laser Doppler velocimetry. Measurements were conducted to quantify the vortex swirl velocity components, the inner core development, and the overall vortical flow inside the vortex trails. The results were then compared to a baseline blade with a standard unmodified rectangular tip. It was found that the slotted blade reduced the peak value of the swirl velocity components in the tip vortex by up to 60% relative to those of the baseline blade. The core growth of the tip vortices from the slotted blade suggested a much higher rate of diffusion, up to as much as three times that of the baseline case. Measurements of rotor power showed only a 3% increase relative to the baseline tip. Based on the overall results, the slotted blade is considered a highly effective design in diffusing vorticity and reducing the flow high field velocities that would otherwise be induced by a rotor tip vortex.

Han, Y. O. and Leishman, J. G. and Coyne, A. J.

"MEASUREMENTS OF THE VELOCITY AND TURBULENCE STRUCTURE OF A ROTOR TIP VORTEX"

AIAA Journal, Vol. 35, No. 3, March 1997, pp. 477-485

The turbulent flow structure of a tip vortex generated by a hovering rotor was investigated with the use of three-dimensional laser Doppler velocimetry. The velocity field was measured at five wake ages, with the three components of turbulence being measured at the three earliest ages. The tangential

(swirl) velocity component inside the tip vortex was found to have a self-similar behavior for all wake ages. The viscous core size was estimated to be approximately 2.5% of the blade chord just after formation, growing with the square root of vortex age to about 13% of blade chord at one rotor revolution. At early wake ages, radially symmetric peaks in the turbulence intensities were measured inside the vortex core, whereas only a single peak appeared in the turbulence distribution at later ages. The radial component of turbulence was found to be the most dominant, with the axial component being the smallest. Additional turbulence quantities, such as Reynolds' stress, were also measured. Finally, the evolutionary features of the turbulent kinetic energy production are discussed.

Hancock, G. J.

"A REVIEW OF THE AERODYNAMICS OF A JET IN A CROSS FLOW"

Aeronautical Journal, May 1987, pp. 201-213.

The aerodynamics of a circular jet emerging normally from a wall into a cross flow is critically assessed. Some general trends are obtained when viscous effects are neglected. Attempts to predict these real effects are reviewed and their anomalies highlighted. The importance of understanding and specifying the jet exit conditions is stressed, which is relevant to complete numerical solutions.

Hancock, G. J.

"AERODYNAMIC LOADING INDUCED ON A TWO-DIMENSIONAL WING BY A FREE VORTEX IN INCOMPRESSIBLE FLOW"

The Aeronautical Journal of the Royal Aeronautical Society, Vol. 75, June 1971, pp. 413-416.

Practical problems often arise in which the aerodynamic loadings on wings and fins, due to nearby free vortices, are required. For example, aerodynamic loads on helicopter blades are affected by the tip vortices which are continuously being shed and which lie beneath the rotor plane. And vortices shed from the nose of an aircraft fuselage can induce significant side loads on a fin. The estimation of the aerodynamic load distribution on a moving wing in the neighborhood of a free vortex (whose axis is primarily in the free stream direction) is an interesting problem which, as far as the author is aware, has not been discussed previously in the literature. Standard techniques for conventional linearized wing theory cannot be applied directly to this problem because the trailing vorticity shed from the wing trailing edge is affected by the flow field of the free vortex and so the mathematical application of the Kutta trailing edge condition is more complex. In this note the loading is estimated on a two-dimensional wing at zero incidence at low speeds due to a free line vortex, lying above the wing, whose axis is primarily in the free stream direction. The problem is three-dimensional. The loading on the wing is due to two primary effects. First the circulatory motion about the free vortex induces an asymmetric distribution of downwash (i.e. upwash on one side of the free vortex, downwash on the other side) which in turn induces an asymmetric spanwise load distribution, the loading will tend asymptotically to zero at large spanwise distances from the vortex. Second, the sidewash velocities induced on the wing upper surface by the free vortex will induce a 'suction' loading, this loading will be

symmetric on either side of the free vortex, and, in general, it will be a local effect. It is assumed that the rate of change of spanwise loading is small so that a 'lifting line' approximation can be made. A series solution, based essentially on a power series in terms of the strength of the free vortex, is set up which incidentally satisfies the trailing edge Kutta condition. Assuming that the velocities induced by the free vortex in the neighborhood of the wing are small, the first two terms in the series solution are sufficient to indicate the loading. The solution for a free vortex very close to the wing is not obtained. There are mutual interference effects between the free vortex and the wing vorticity. The wing vorticity will induce a flow field in the neighborhood of the free vortex, so the free vortex will curve to follow the local streamline direction. An estimation of this effect is given.

Hancock, G. J.

"ON THE ROLLING UP OF A TRAILING VORTEX SHEET"

Aero. Journal, Vol. 74, No. 717, September 1970, pp. 749-752

This paper looked at the rollup of two vortices behind a wing with an elliptical spanwise load distribution when the standard linear model becomes less valid, for example, at higher wing lift coefficients. The paper assumed that a continuous trailing vortex sheet rolls up into two discrete vortices, and this rolling up process takes place far downstream of the finite wing which generates the trailing vorticity.

Hancock, P. E., Zhang, S., Pascheke, F. and Hayden, P.

"WIND TUNNEL SIMULATION OF A WIND TURBINE WAKE IN NEUTRAL, STABLE AND UNSTABLE WIND FLOW"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012047-1 - 012047-11.

Measurements of mean velocity, Reynolds stresses, temperature and heat flux have been made in the wake of a model wind turbine in the EnFlo meteorology wind tunnel, for three atmospheric boundary layer states: the base-line neutral case, stable and unstable. The full-to-model scale is approximately 300:1. Primary instrumentation is two-component LDA combine with cold-wire thermometry to measure heat flux. In terms of surface conditions, the stratified cases are weak, but there is a strong 'imposed' condition in the stable case. The measurements were made between 0.5D and 10D, where D is the turbine disk diameter. In the stable case the velocity deficit decreases more slowly; more quickly in the unstable case. Heights at which quantities are maximum or minimum are greater in the unstable case and smaller in the stable case. In the stable case the wake height is suppressed but the width is increased, while in the unstable case the height is increased and the width (at hub height) reaches a maximum and then decreases. The turbulence in the wake behaves in a complex way. Further work needs to be done, to cover stronger levels of surface condition, requiring more extensive measurements to properly capture the wake development.

Handley, W. A.

"TWO NEXTGEN AIR SAFETY TOOLS: AN ADS-B EQUIPPED UAV AND A WAKE TURBULENCE ESTIMATOR"

MS Thesis, 2016, University of Washington, Seattle, WA.

Two air safety tools are developed in the context of the FAA's NextGen program. The first tool addresses the alarming increase in the frequency of near-collisions between manned and unmanned aircraft by equipping a common hobby class UAV with an ADS-B transponder that broadcasts its position, speed, heading and unique identification number to all local air traffic. The second tool estimates and outputs the location of dangerous wake vortex corridors in real time based on the ADS-B data collected and processed using a custom software package developed for this project. The TRansponder based Position Information System (TRAPIS) consists of data packet decoders, an aircraft database, Graphical User Interface (GUI) and the wake vortex extension application. Output from TRAPIS can be visualized in Google Earth and alleviates the problem of pilots being left to imagine where invisible wake vortex corridors are based solely on intuition or verbal warnings from ATC. The result of these two tools is the increased situational awareness, and hence safety, of human pilots in the National Airspace System (NAS).

Hannon, S. M.

"PULSED DOPPLER LIDAR FOR TERMINAL AREA MONITORING OF WIND AND WAKE HAZARDS"

AMS Conference, Hyannis, MA, October 2004.

CLR has made significant improvements in its solid-state 2-micron pulsed Doppler lidar systems over the past decade. For the past two years, one of our Doppler lidars has been operating at the Hong-Kong International Airport for windshear and turbulence detection. Another dedicated unit has been installed for more than a year at the St. Louis International Airport for FAA-sponsored, long-term wake vortex monitoring. These installations demonstrate significantly different means by which the same technology can benefit airport operations.

Hannon, S. M.

"TRACK FORMAT DESCRIPTION FOR PULSED DOPPLER LIDAR MEASUREMENTS OF WAKE VORTICES AT DENVER INTERNATIONAL AIRPORT"

Report, April 2004, CLR Photonics, Inc., Lafayette, CO.

This document describes the format for the ASCII wake vortex track output produced by the WindTracer pulsed Doppler lidar at the 2003 NASA-sponsored Denver International Airport Wake Acoustic Tests. The Wake Acoustic Tests were conducted on the north end of Denver International Airport (DIA) in August and September, 2003. This document comprises five sections. Section 2 provides a concise description of the lidar used during the test and an overview of the real-time wake vortex detection and tracking algorithm. Various parameters are defined. The lidar coordinate system for the measurements is illustrated in Section 3. Section 4 summarizes the database. Section 5 provides

representative plots of the vortex attributes (positions and circulation) along with the associated lidar-measured crosswind profiles.

Hannon, S. M.

"AUTONOMOUS INFRARED DOPPLER RADAR: AIRPORT SURVEILLANCE APPLICATIONS"

Proceeding First European Conference on Radar Meteorology, September 2000, Bologna, Italy, pp. 1-7.

Infrared Doppler radar (Doppler lidar) sensors provide a unique capability to generate high resolution, three-dimensional distributions of wind and aerosol data. Appropriately processed, these data can be used in the airport terminal area to map hazardous wind shear and turbulence levels, detect and track wake vortices, and monitor slant path visibility. The benefit of the infrared radar relative to its microwave counterparts is the ability to sense clear air hazards, especially those in and around local terrain features. The fact that the infrared radar beam is quite narrow significantly reduces, if not eliminates, artifacts associated with sidelobe-induced ground clutter. Continued rapid developments in the arena of solid-state infrared Doppler radar have yielded substantial advancements in terms of autonomous, stand-alone operation. Such developments have made possible the ability to deploy compact and robust systems that are unattended. This paper summarizes our autonomous pulsed lidar developments and reviews sample results.

Hannon, S. M.

"DETECTION AND TRACKING OF WAKE VORTICES WITHIN APPROACH AND DEPARTURE CORRIDORS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001.

Pulsed infrared Doppler radar (Doppler lidar) sensors provide a unique capability to generate high resolution, three-dimensional distributions of wind data. Appropriately processed, these data can be used in the airport terminal area to map hazardous wind shear and turbulence levels and to detect and track wake vortices. Within the past five years, continued rapid developments in the arena of solid-state infrared Doppler radar have yielded substantial advancements in terms of autonomous, stand-alone operation. Such developments have made possible the ability to deploy compact and robust systems that are unattended. For certain operational scenarios and procedures designed to improve capacity, the lidar can provide needed wake vortex detection and tracking observations within the approach and departure corridors. This presentation summarizes autonomous pulsed lidar developments and reviews results from recent relevant deployments.

Hannon, S. M. and Henderson, S. W.

"WIND MEASUREMENT APPLICATIONS OF COHERENT LIDAR"

The Review of Laser Engineering, Vol. 23, No. 2, February 1995, pp. 124-130

Pulsed solid-state coherent laser radar (lidar) systems are rapidly evolving as useful sensors for a variety of ground-based and airborne measurement applications. This paper describes such measurement applications and sample demonstration measurement results associated with wake vortex detection and tracking, windshear and gust front detection, and wind field monitoring in support of Space Shuttle operations.

Hannon, S. M. and Pelk, J. V.

"PULSED DOPPLER LIDAR MEASUREMENTS OF WAKE VORTICES AT THE SAN FRANCISCO INTERNATIONAL AIRPORT"

Report CTI-TR-2002-04, February 2002, Coherent Technologies, Inc., Lafayette, CO.

This report summarizes results of a September 2001 program in which a WindTracer 2-m pulsed coherent Doppler lidar was deployed to the San Francisco International Airport (SFO). For historical reference, this was the first large scale pulsed lidar based wake turbulence dataset of the Federal Aviation Administration (FAA) Wake Turbulence Research Program. The focus of the wake vortex measurements was to collect data that can be used for comparison with other sensors (e.g., the Volpe windline and sodar) and/or model predictions (ASAT, the Airspace Analysis Tool). In a more general sense, the program supports the FAA Wake Turbulence Research Program which endeavors to improve airport capacity by addressing various issues associated with aircraft wake vortices.

Hannon, S. M. and Pelk, J. V.

"PULSED DOPPLER LIDAR MEASUREMENTS OF WAKE VORTICES AT THE SAN FRANCISCO INTERNATIONAL AIRPORT"

CTI-TR-2002-04, February 2002, Coherent Technologies, Inc., Lafayette, CO

A Wind Tracer pulsed coherent Doppler lidar has been used to generate a large, high-quality database of wake vortex behavior at the San Francisco International Airport. More than 2400 vortex track files have been generated. Vortex behavior out of ground effect (OGE) and in ground effect (IGE) was observed during a 2.5-week period in September 2001. In addition to the vortex track files, the database includes 420 PPI wind scans and 438 vertical wind profiles. These data can be used to significantly enhance the meteorological database at SFO and, in particular, to quantify turbulence level and overall wind variability. The SFO deployment was successful in demonstrating several key firsts for pulsed Doppler lidar: Simultaneous detection and tracking of aircraft vortices for paired approaches, Simultaneous observation of wake vortices along multiple points on the approach glide slope, and Unattended (i.e., no operator) detection and tracking of wake vortices.

Hannon, S. M. and Thomson, J. A.

"WAKE VORTEX DETECTION AT DENVER STAPLETON AIRPORT WITH A PULSED 2-MICRON COHERENT LIDAR;"

Airborne Windshear Detection and Warning Systems - Fifth and Final Combined Manufacturers' and Technologists' Conference, DOT/FAA/RD-94/14-II, Langley Research Center, Hampton, VA, July 1994, pp. 62.

This report describes the effort undertaken to relate aircraft wake history to the local environment. This involved the monitoring of the embedded wind field, monitoring of local meteorological parameters, a high-resolution velocity field analysis in vertical scan planes and measurement of the axial velocity signature. A flashlight pumped 2.09- micron solid state coherent laser radar system was used to detect and track wake vortices. Strong wake vortex signatures were measured for moderate to large aircraft at Denver's Stapleton airport and a large vortex database was compiled.

Hannon, S. M. and Thomson, J. A.

"AIRCRAFT WAKE VORTEX DETECTION AND MEASUREMENT WITH PULSED SOLID-STATE COHERENT LASER RADAR"

J. Modern Optics, Vol. 41, No. 11, November 1994, pp. 2175-2196

Pulsed solid-state coherent laser radar (lidar) systems can measure radial wind velocity to precision well below 1 m/s at spatial scales on the order of 30-50 m and to ranges of several kilometers. This capability is appropriate for a variety of measurement objectives in the airport terminal area. Wake vortex detection and tracking is one of the primary objectives currently being evaluated by regulatory agencies in the United States and elsewhere. Up to now, noninvasive measurement of wake vortex properties as been limited to short-range continuous-wave lidar systems. This paper discusses this application and presents theoretical analysis and experimental results for 21m coherent lidar. Detection, tracking, and measurement results are presented for sample DC-10, 757, and 727 aircraft landings from a laser radar wake vortex database compiled in 1993 at Denver Stapleton International Airport.

Hannon, S. M., Barr, K. S., Jacob, D. K. and Phillips, M. W.

"APPLICATION OF PULSED DOPPLER LIDAR IN THE AIRPORT TERMINAL AREA"

Proceedings of SPIE, Vol. 5653, 2005, pp. 186-197

Pulsed coherent Doppler lidar systems have matured rapidly, especially at solid-state wavelengths. Turnkey systems are commercially available and are being deployed for various aviation applications. Doppler lidar data is used in the airport terminal area to map hazardous wind shear and turbulence levels and to detect and track wake vortices. Future applications could include slant path visibility monitoring. Several permanent installations and rapidly deployable instrument configurations have been achieved. The benefit of the infrared Doppler lidar relative to its microwave counterparts is the ability to sense clear air hazards, especially those in and around local terrain features. The fact that the lidar beam is quite narrow eliminates artifacts associated with sidelobe-induced ground clutter. This paper summarizes our autonomous pulsed lidar developments and reviews sample results.

Hannon, S. M., Phillips, M. W., Thomson, J. A. and Henderson, S. W.

"PULSED COHERENT LIDAR WAKE VORTEX DETECTION, TRACKING AND STRENGTH ESTIMATION IN SUPPORT OF AVOSS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 261-279

This paper summarizes NASA- and Air-Force-supported development and field deployment activities underway at CTI in the area of pulsed 2- micron coherent lidar for wake vortex detection and tracking. The laser transceiver and real-time signal processor are described. Algorithm validation activities are summarized. Estimated circulation strength estimates are compared with model predictions and are shown to be quite reasonable.

Hannon, S. M., Thomson, J. A., Henderson, J. A. and Huffaker, R. M.

"WINDSHEAR, TURBULENCE AND WAKE VORTEX CHARACTERIZATION USING PULSED SOLID-STATE COHERENT LIDAR"

Proceedings of the Conference, Air Traffic Control Technologies, Orlando, FL, April 18-19, 1995, Society of Photo-Optical Instrumentation Engineers (SPIE) Proceedings, Vol. 2464, 1995, pp. 94-10.

Coherent lidar systems based on eye-safe solid-state laser technology are rapidly emerging in ruggedized packages. The airport terminal area presents several measurement scenarios appropriate for application of pulsed coherent lidar sensors. This paper briefly reviews the status of coherent lidar technology and presents results produced with a mobile flashlamp-pumped 2.09-micron coherent lidar sensor for windshear detection and measurement, wind turbulence estimation, and wake vortex detection and tracking.

Hansen, J. L. and Cobleigh, B. R.

"INDUCED MOMENT EFFECTS OF FORMATION FLIGHT USING TWO F/A-18 AIRCRAFT"

NASA/TM-2002-210732, August 2002, NASA Dryden Flight Research Center, Edwards, CA.

Previous investigations into formation flight have shown the possibility for significant fuel savings through drag reduction. Using two F/A-18 aircraft, NASA Dryden Flight Research Center has investigated flying aircraft in autonomous formation. Positioning the trailing airplane for best drag reduction requires investigation of the wingtip vortex effects induced by the leading airplane. A full accounting of the vortex effect on the trailing airplane is desired to validate vortex-effect prediction methods and provide a database for the design of a formation flight autopilot. A recent flight phase has mapped the complete wingtip vortex effects at two flight conditions with the trailing airplane at varying distances behind the leading one. Force and moment data at Mach 0.56 and an altitude of 25,000 ft and Mach 0.86 and an altitude of 36,000 ft have been obtained with 20, 55, 110, and 190 ft of

longitudinal distance between the aircraft. The moments induced by the vortex on the trailing airplane were well within the pilot's ability to control. This report discusses the data analysis methods and vortex-induced effects on moments and side force. An assessment of the impact of the nonlinear vortex effects on the design of a formation autopilot is offered.

Hanses, C., Knabe, F. and Korn, B.

"DESIGNING AND EVALUATING ADVANCED APPROACH PROCEDURES FOR THE CONCEPT OF SEGMENTED INDEPENDENT PARALLEL APPROACHES"

AIAA Paper 2015-2431, June 2015, Dallas, TX.

From the perspective of flight guidance, the development of laterally segmented or curved approach procedures that allow for rerouting around congested areas is a promising strategy for coping with noise issues. At major airport-hubs with parallel runway systems, airport capacity needs to be considered as well; for those airports, an increased capacity can be reached when runways are operated independently. This, however, requires straight precision approaches according to current guidelines issued by the International Civil Aviation Organization (ICAO). To help pave the way for independent operations of segmented approaches at airports with parallel runway systems, an elementary safety concept is summarized in this work. Moreover, a procedure design developed to participate from benefits of laterally segmented approach procedures will be presented and evaluated with respect to capacity implications.

Hanson, C. E.

"AN INVESTIGATION OF THE NEAR WAKE PROPERTIES ASSOCIATED WITH PERIODIC VORTEX SHEDDING FROM AIRFOILS"

AVL Report 76234-5, September 1970, Mass. Institute of Technology, Cambridge, MA

An investigation of the near wake of airfoils with various trailing edge configurations including splitter plates reveals properties which are conducive to wake periodicity. The frequency of the shedding process is found to scale with the new wake momentum thickness and a wake velocity simply related to the base pressure coefficient. Computer results suggest that the frequency and bandwidth of the vortex shedding process can be predicted by a solution of the complete Orr-Sommerfeld equation.

Hanson, C., Andrade, S. and Pable, J.

"EXPERIMENTAL MEASUREMENTS OF PASSENGER RIDE QUALITY DURING AIRCRAFT WAKE SURFING"

AIAA Paper 2018-3561, June 2018, Atlanta, GA.

The National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center completed a series of research flights to better understand the challenges of aircraft wake surfing using civilian airplanes and commercial avionics. Airlines and air cargo carriers have identified uncertainty

about increased passenger/crew discomfort due to noise and vibrations as a potential obstacle to the widespread adoption of aircraft wake surfing. To measure the effects of wake surfing on passenger ride quality, NASA instrumented a business jet with cabin noise and vibration sensors. The airplane was then flown under control of an experimental autopilot at multiple locations within the wake of a similar airplane. This paper presents a summary of the measurements collected on these flights, an assessment of passenger discomfort correlated with wake surfing performance benefits, and qualitative evaluations collected from passengers aboard during the research flights.

Hanson, C., Pahle, J., Reynolds, J., Andrade, S. and Brown, N.

"EXPERIMENTAL MEASUREMENTS OF FUEL SAVINGS DURING AIRCRAFT WAKE SURFING"

AIAA Paper 2018-3560, June 2018, Atlanta, GA.

The National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (Edwards, California) completed a series of research flights to better understand the challenges of aircraft wake surfing using civilian airplanes and commercial avionics. The research flights sought to demonstrate significant fuel savings by a pair of business jets engaged in automated wake surfing using commercial off-the-shelf avionics to the fullest extent possible, including a 1090-MHz Automatic Dependent Surveillance - Broadcast (ADS-B) data link. A NASA Gulfstream C-20A airplane (Gulfstream Aerospace, Savannah, Georgia) was flown as the trail airplane within the wake of a NASA Gulfstream III (G-III) airplane. This paper presents a summary of the fuel savings measured during these flights.

Hanson, H. M. and Hanson, D. M.

"A REEXAMINATION OF THE FORMATION OF EXHAUST CONDENSATION TRAILS BY JET AIRCRAFT"

Journal of Applied Meteorology, Vol. 34, November 1995, pp. 2400-2405.

With the end of World War II, it became apparent that a study should be undertaken to identify the factors controlling the production of aircraft condensation trails (contrails). This early work provided a theoretical prediction of the critical temperature at which the values of the relative humidity and pressure are such that the formation of the contrail phenomenon will occur. As empirical data were obtained, the general agreement at increased altitude was not precise and several studies were made to obtain both theoretical and empirical fits that would provide a 'yes/no' decision. These modifications did allow a better decision for the formation of contrails but were found to be increasingly inaccurate at greater altitudes. This study provides an improved algorithm that yields a theoretical prediction that is in general agreement with the available empirical data at all altitudes. It demonstrates that there is a need for additional effort in the identification and precision of relative humidity and pressure that are input to this computation.

Hanson, H.-E.

"JAS 39 GRIPEN. WAKE VORTEX PENETRATION FLIGHT TESTING"

Proceedings of the 17th SFTE Symposium, Amsterdam, The Netherlands, June 2006

JAS 39 Gripen is basically a highly unstable aircraft in pitch in the subsonic Mach region. Pitch static stability is obtained by means of AoA vane feedback. For optimum control during demanding control tasks, a blend of proportional vane signal and complementary filtered AoA was selected. However, the good control characteristics were achieved at the cost of some sensitivity to vortex transients. The very robust AoA MLL function in the control laws entice pilots to sustained max commands below corner speed and thereby expose the aircraft to a vulnerable condition for Wake Vortex disturbances. After a number of Wake Vortex Related incidents in SwAF service there was an obvious need for a new control law. A new flight control system edition was developed and tested in large batch simulations of more than 12000 wake vortex passages to prove that the new flight control system edition had significant effect on transient reduction during a Wake Vortex passage. This paper describes the Gripen Vortex penetration and propwash flight test program performed during 2005 and 2006 at Saab in Linkoping, Sweden.

Hanson, J. M. and Marcotte, F. J.

"AIRCRAFT WAKE VORTEX DETECTION USING CONTINUOUS-WAVE RADAR"

Johns Hopkins APL Technical Digest, Vol. 18, No. 3, 1997, pp. 348-357.

The Applied Physics Laboratory designed and constructed a bistatic continuous-wave radar system for experiments in aircraft wake vortex detection. Acoustic pumping was evaluated as a possible technique to enhance overall performance. The radar and acoustic systems were installed at the Baltimore-Washington International Airport in the fall of 1996. Controlled experiments using a NASA C-130 aircraft are discussed, and some preliminary results are presented.

Hanson, T.

"A WAY OUT OF THE WAKE"

Professional Pilot, Vol. 30, No. 6, June 1996, pp. 54-59.

The search for an affordable wake-turbulence-avoidance system.

Hardin, J. C.

"THE VELOCITY FIELD INDUCED BY A HELICAL VORTEX FILAMENT"

Physics of Fluids, Vol. 25, No. 11, November 1982, pp. 1949-1952.

An exact analytical solution for the velocity field, both interior and exterior, induced by an infinite right-handed helical vortex filament is derived. Due to the way the variables combine in this solution, the paper also shows that it is possible to derive a stream function for this non-axisymmetric flow. Sample calculations of these expressions are included.

Hardin, J. C.

"NOISE RADIATION FROM THE SIDE EDGES OF FLAPS"

AIAA Journal, Vol. 18, No. 5, May 1980, pp. 549-552.

The recently observed phenomenon of high noise radiation from the side edges of flaps in flow is investigated by way of a simple two-dimensional model problem. The model is based upon a physical picture of boundary layer vorticity being swept around the edge by spanwise flow on the flap. The model problem is developed and solved and the resulting noise radiation calculated. Further, a mathematical condition for the vortex to be captured by the potential flow and swept around the edge is derived. The results show that the sound generation depends strongly upon the strength of the vorticity and distance from the edge and that it can be more intense than the more common trailing edge noise source in agreement with the experimental observations.

Hardin, J. C. and Wang, F. Y.

"SOUND GENERATION BY AIRCRAFT WAKE VORTICES"

NASA-CR-2003-212674, December 2003, NASA Langley Research Center, Hampton, VA.

This report provides an extensive analysis of potential wake vortex noise sources that might be utilized to aid in their tracking. Several possible mechanisms of aircraft vortex sound generation are examined based on discrete vortex dynamic models and characteristic acoustic signatures calculated by application of vortex sound theory. It is shown that the most robust mechanisms result in very low frequency infrasound. An instability of the vortex core structure is discussed and shown to be a possible mechanism for generating higher frequency sound bordering the audible frequency range. However, the frequencies produced are still low and cannot explain the reasonably high-pitched sound that has occasionally been observed experimentally. Since the robust mechanisms appear to generate only very low frequency sound, infrasonic tracking of the vortices may be warranted.

Hardin, J. C., Gilinsky, M. and Khaikine, V.

"ESTIMATION OF THE LOCATION OF A FARFIELD ACOUSTIC SOURCE"

J. Acoustical Soc. America, Vol. 118, July 2005, pp. 45-50

A backward integration method for estimating the location of a source of sound waves in the atmosphere is presented. This geometric acoustics method is based upon the analysis of microphone array measurements to determine the incoming ray direction in three dimensions. The equations governing the propagation of the ray are then integrated backward in time. The sound source lies somewhere along the calculated ray path. The intersection of such loci from more than one array would provide an estimate of the source location. The method appears to be very rapid to implement

and, assuming the time delays to be accurately measured, limited in accuracy only by the timeliness of the input sound speed and velocity profiles in the atmosphere.

Hardin, J. C., Wang, F. Y. and Wassaf, H.

"SOUND GENERATION BY AIRCRAFT WAKE VORTICES INTERACTING WITH THE GROUND PLANE"

AIAA Paper No. 2004-2881, Manchester, UK, May 2004

This paper examines the acoustic radiation produced by the interaction of aircraft wake vortices with the ground plane. The wake vortices are modeled as vortex filaments of finite length and the theory of vortex sound is applied to calculate the resulting noise generation. A new expression for evaluating the retarded time integrals in this geometry is developed. An example is presented which illustrates that the sound generation by this source for commercial aircraft is generally infrasonic. In addition, a comparison of the sound pressure time histories with and without taking retarded time differences into account is presented. It is determined that, for the case of wake vortex-ground interaction, retarded time differences can be ignored, thereby allowing more efficient computation.

Hardy, G. H. and Lewis, E. K.

"COCKPIT DISPLAY OF TRAFFIC AND WAKE INFORMATION FOR CLOSELY SPACED PARALLEL APPROACHES"

AIAA Paper No. 2004-5106, Providence, RI, August 2004.

A preliminary study of a Cockpit Display of Traffic and Wake Information for closely spaced parallel approaches was conducted at the NASA Ames Research Center. With the advent of the navigational precision of the Global Position System, data-link, and the operational procedures of Required Navigational Performance, the possibility exists for simultaneous instrument operations to runways with separations approaching those used for simultaneous visual operations. In addition, new algorithms for predicting wake vortex movement may allow these instrument operations to be conducted with greater safety than for present visual operations. The study developed a cockpit display for traffic and wake information and developed operational procedures for a mix of conventional and runway independent aircraft to closely spaced landing areas. Results showed that very small Total System Errors were obtained using pursuit displays and manual flight control. For aircraft with different approach speeds, a small increase in paired aircraft approach spacing was found to be necessary for wake separation over that for aircraft with similar approach speeds. Performance at decision height was compatible with CAT II/IIIA operations.

Hariharan, N.

"ROTARY-WING WAKE CAPTURING: HIGH-ORDER SCHEMES TOWARD MINIMIZING NUMERICAL VORTEX DISSIPATION"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 822-829

The use of high-order, first-principles-based Euler/Navier-Stokes methodologies for rotary-wing wake capturing is assessed. Fifth/seventh-order spatially accurate essentially non-oscillatory methodologies were implemented and their benefits in capturing wake vortices were addressed. The use of high-order solution reconstruction, in conjunction with the use of overset grids to resolve selectively regions of interest such as concentrated vorticity, was also explored. The tip vortex off of a NACA0015 wing was captured using this methodology, and the tip vortex characteristics are compared with experiments. The relative merits of fifth- and seventh-order schemes are assessed for capturing wake vorticity.

Hariharan, N. and Sankar, L.

"UNIFORMLY HIGH-ORDER ESSENTIALLY NONOSCILLATORY SCHEMES FOR VORTEX CONVECTION ACROSS OVERSET INTERFACES"

J. Aircraft, Vol. 45, No. 2, March-April 2008, pp. 546-559

The construction of uniformly high-order accurate numerical schemes based on an essentially non-oscillatory methodology was considered in this work. In particular, the accuracy of essentially non-oscillatory scheme implementations near the interface boundaries for overset grids was analyzed. Essentially non-oscillatory schemes use large stencil support for constructing progressively high-order accuracy spatial schemes. The handling of such schemes near overset boundaries influences the overall solution accuracy for large-scale computations. An essentially non-oscillatory based 5th/7th order spatially accurate Euler/Navier-Stokes overset solver was used to study the convection of vortices across overset interfaces. Three different numerical formulations near the boundary interfaces were studied. Two overlapping Cartesian meshes were generated, and a Lamb's vortex was convected across the overset interface between the two meshes. The fidelity of the vortex as it crossed the interface was analyzed, and the results were compared for the three near-boundary formulations. It was found that the preservation of the vortex strength crucially depended upon the correct formulation and interpolation of high-order fluxes within the essentially non-oscillatory framework near the overset interface.

Hariharan, N. and Sankar, L. N.

"A REVIEW OF COMPUTATIONAL TECHNIQUES FOR ROTOR WAKE MODELING"

AIAA Paper No. 2000-0114, Reno, NV, 2000

This paper discusses existing techniques for modeling the rotor wake in hover and in forward flight. It also briefly reviews extensions of these methods for modeling complete rotorcraft. The review is followed by results from promising high order overset methods for wake capturing, and efficient hybrid near field Navier-Stokes wake capturing/far-field potential flow wake convecting methodologies. The paper concludes with some speculations on the likely advances in rotorcraft flow field modeling in the forthcoming years.

Hariharan, N. and Sankar, L. N.

"HIGH-ORDER ESSENTIALLY NONOSCILLATORY SCHEMES FOR ROTARY-WING WAKE COMPUTATIONS"

Journal of Aircraft, Vol. 41, No. 2, March-April 2004, pp. 258-267

The use of fifth-seventh-order spatially accurate, essentially non-oscillatory (ENO) schemes for capturing vortices using Euler/Navier-Stokes equations is discussed. These schemes are constructed to minimize numerical dissipation and are evaluated for their application to flow fields laden with vorticity. The fifth-order ENO scheme is compared with a commonly used third-order MUSCL scheme for a two-bladed rotor in hover. Based on the results, the fifth- and seventh-order ENO schemes are evaluated for their ability to convect a vortex generated from a wing tip. The relative merits of these schemes for capturing vortex wakes arising from wings and rotor blades are summarized.

Hariharan, N. S.

"A HIGH ORDER OVERSET REFINEMENT METHODOLOGY FOR VORTEX-DOMINATED FLOWFIELD STUDIES"

AIAA Paper No. 2002-0965, Reston, VA, April 2002

A high order methodology with vortex-tracking overset refinement for the use in vorticity dominated flow fields is explored in this effort. The stimulus for this work arises from efforts to capture the tip vortex of a rotor-blade using first-principles based Euler/Navier-Stokes methods. High order solution reconstruction in conjunction with moving 'tracking' overset grid is used to selectively resolve required regions of interests such as concentrated vorticity. Vortex capturing using a wing grid-vortex grid overset system was undertaken using a baseline fifth/seventh order spatial/third order temporal ENO scheme. A system to automatically re-shape the vortex grid to conform to the vortex shape as the solution evolves was developed and tested. The methodology was found to work well when the vortex system is well defined, i.e., rotor-blade, wing tip vortex system.

Hariharan, N., Egolf, A. and Sankar, L.

"SIMULATION OF ROTOR IN HOVER: CURRENT STATE AND CHALLENGES"

AIAA Paper 2014-0041, January 2014, National Harbor, MD.

A helicopter is subjected to a wide variety of flight conditions with disparate objectives; these include efficient cruise and hover, and high-performance maneuvering. The hover condition remains a very important design consideration because it represents the true value of the helicopter, and it is a limiting design point in terms of power requirements. Accurate numerical prediction of rotor-blade aerodynamic parameters such as thrust, torque and efficiency, requires an accurate modeling of the vortex wake. Despite tremendous advancements in the ability to preserve the tip vortex from first principles, the capability to consistently and reliably predict performance parameters for a new rotor-

blade has still been elusive. These challenges provide the motivation for the AIAA Applied Aerodynamics Technical Committee Rotorcraft Simulation Working Group's efforts to evaluate hover simulation capabilities across government organizations, industry, and academia. The AIAA Applied Aerodynamics Rotor Simulation Working Group aims to bring together government, industry, and academic participants to evaluate and further rotor-in-hover performance predictions. The invited session at SciTech 2014 is the first step to assess different approaches for the prediction of baseline S-76 rotor planform. Future plans include a full workshop at SciTech 2015 to evaluate prediction of performance for S-76 planforms with various tip-shapes.

Hariharan, N., Wissink, A. and Steffen, M.

"TIP VORTEX FIELD RESOLUTION USING AN ADAPTIVE DUAL-MESH COMPUTATIONAL PARADIGM"

AIAA Paper No. 2011-1108, January 2011, Orlando, FL.

This paper describes the efforts to model vorticity laden flow fields using the CREATE-AV Helios platform. Helios employs a dual-mesh paradigm: near body unstructured grids, and high order accurate off-body Cartesian grids, and information exchange is facilitated by an automated, implicit hole cutting method. Further, an automatic mesh refinement capability is employed to refine regions of intense vorticity. Two different scenarios are considered: (a) the vortical flow field off a high-angle-of-attack aircraft, (b) the helical wake of a model rotor in hover. The ease of use, efficiency, and power of the Helios dual-mesh paradigm is demonstrated through high fidelity solutions for the aforementioned unsteady vortical fields.

Harland, R. B. and Madden, S. J.

"A HAZARD DEFINITION FOR WAKE TURBULENCE ENCOUNTER DURING TERMINAL AREA OPERATIONS"

RE-81, March 1973, Mass. Institute of Technology, Cambridge, MA

A six-degree-of-freedom vortex encounter simulation has been developed for use on a hybrid computer to determine the hazard potential for terminal area operations. Complete trajectory data for landing, horizontal flyby, and climbing flights are presented and conclusions are drawn from these results. A hazardous condition is defined as having the roll angle exceed ten degrees and/or the flight path angle become steeper than -4.5 degrees at any point along the flight path with the aircraft under autopilot control. A simplified sensitivity analysis shows that the controllability of an aircraft is about twice as sensitive to changes in vortex proximity than to changes in wingspan, but if the near wingtip proximity is chosen to be the independent variable, controllability is nearly independent of aircraft size.

Harrington, R. F.

"FEASIBILITY OF DETECTING AIRCRAFT WAKE VORTICES USING PASSIVE MICROWAVE RADIOMETERS"

NASA-CR-191553, December 1993, Old Dominion Univ., Norfolk, VA

The feasibility of detecting the cold core of the wake vortex from the wingtips of an aircraft using a passive microwave radiometer was investigated. It was determined that there is a possibility that a cold core whose physical temperature drop is 10 C or greater and which has a diameter of 5 m or greater can be detected by a microwave radiometer. The radiometer would be a noise injection balanced Dicke radiometer operating at a center frequency of 60 GHz. It would require a noise figure of 5 dB, a pre-detection bandwidth of 6 GHz, and an integration time of 2 seconds resulting in a radiometric sensitivity of 0.018 K. However, three additional studies are required. The first would determine what are the fluctuations in the radiometric antenna temperature due to short-term fluctuations in atmospheric pressure, temperature, and relative humidity. Second, what is the effect of the pressure and temperature drop within the cold core of the wake vortex on its opacity. The third area concerns the possibility of developing a 60 GHz radiometer with a radio metric sensitivity an order of magnitude improvement over the existing state of the art.

Harris, D. M. and Williamson, C. H. K.

"INSTABILITY OF SECONDARY VORTICES GENERATED BY A VORTEX PAIR IN GROUND EFFECT"

Journal of Fluid Mechanics, Vol. 700, 2012, pp. 148-186.

In this work we investigate the approach of a descending vortex pair to a horizontal ground plane. As in previous studies, the primary vortices exhibit a rebound, due to the separation of secondary opposite-sign vortices underneath each primary vortex. On each side of the flow, the weaker secondary vortex can become three-dimensionally unstable, as it advects around the stronger primary vortex. It has been suggested in several recent numerical simulations that elliptic instability is the origin of such waviness in the secondary vortices. In the present research, we employ a technique whereby the primary vortices are visualized separately from the secondary vortices; in fact, we can mark the secondary vortex separation, often leaving the primary vortices invisible. We find that the vortices are bent in a Crow-type displacement mode, and, by keeping the primary vortices invisible, we can see both sides of the flow simultaneously, showing that the instability perturbations on the secondary vortices are antisymmetric. Triggered by previous research on four-vortex aircraft wake flows, we analyze one half of the flow as an unequal-strength counter-rotating pair, noting that it is essential to consider the angular velocity of the weak vortex around the stronger primary vortex in the analysis. In contrast with previous results for the vortex-ground interaction, we find that the measured secondary vortex wavelength corresponds well with the displacement bending mode, like the Crow-type instability. We have analyzed the elliptic instability modes, by employing the approximate dispersion relation of Le Dizès and Laporte in our problem, finding that the experimental wavelength is distinctly longer than predicted for the higher-order elliptic modes. Finally, we observe that the secondary vortices deform into a distinct waviness along their lengths, and this places two rows of highly stretched vertical segments of the vortices in between the horizontal primary vortices. The two rows of alternating-sign vortices translate towards each other and ultimately merge into a single vortex row. A simple point vortex row model can predict trajectories of such vortex rows, and the net result of the model's orbital or passing modes is to bring like-sign vortices, from each secondary vortex row, close to each other, such that merging may ensue in the experiments.

Harris, D. M., Miller, V. A. and Williamson, C. H. K.

"A SHORT WAVE INSTABILITY CAUSED BY THE APPROACH OF A VORTEX PAIR TO A GROUND PLANE"

Physics of Fluids, Vol. 22, 2010, p. 091106-1.

In the present work, we study the approach of a counter-rotating vortex pair to a ground plane. Between the vortices and the ground, a boundary layer forms, which can separate, to generate secondary vortices of opposite sign (originally discovered by Harvey and Perry). We have developed a novel technique to study this flow in which we pool dye on a horizontal ground plane prior to forming the primary vortex pair, allowing us to principally visualize the secondary vorticity. The secondary vortices begin to develop a three-dimensional instability in the presence of the strain rate field of the primaries. The work here provides a clear visualization of such a periodic phenomenon from experiment, and indicates a distinct phase relationship between the instabilities in the two secondary vortices, leading to interesting subsequent vortex dynamics.

Harris, F. D. and McVeigh, M. A.

"UNIFORM DOWNWASH WITH ROTORS HAVING A FINITE NUMBER OF BLADES"

J. American Helicopter Society, Vol. 21, No. 1, January 1976, pp. 9-20

This paper deals with factors that influence the hovering performance of helicopter rotors. First, a discussion is presented on the short comings of the classical blade element-momentum theory when it is used to define the optimum rotor with a finite number of blades. Fixed-wing aerodynamics theory is used to demonstrate that the loading on a single blade is better represented by treating the rotor blade as a wing in a linearly varying spanwise velocity field. A comparison between experimentally obtained loading on a single blade and the loading calculated from fixed-wing theory is presented. An approximation for the velocity induced by a rolled-up vortex is suggested and comparison of this approximation with a measured velocity distribution near the core region of a tip vortex is shown to be very good.

Harris, M.

"CHALLENGES PAST, PRESENT AND FUTURE FOR LIDAR IN WIND ENERGY"

19th Coherent Laser Radar Conference (CLRC), Paper Th1, June 2018, Okinawa, Japan.

Lidar made its first tentative steps in 2003 towards becoming an accepted tool in the wind industry; significant efforts were needed initially to understand the requirements and establish lidar methods. Important questions were raised, including: is lidar reliable and does it work in all conditions, particularly low backscatter? Is the accuracy sufficient? Can costs be reduced? Today, lidar is used onshore, offshore and on the turbine itself for a range of important activities including resource assessment, power performance evaluation, turbine optimization and active control. The level of acceptance has steadily increased to the point where lidar is now considered mainstream in the growing wind industry, with the development of international standards and roadmaps to bankability.

Remaining challenges include better understanding of complex terrain, wakes and turbulence, and greater acceptance by way of certification and standards. In future new applications may emerge as the technology improves with further cost reductions.

Harris, M.

"FIELD TRIAL MEASUREMENTS OF AIRCRAFT WAKES USING COHERENT LASER RADAR"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Coherent laser radar (or lidar) is a powerful technique for the detection and evaluation of full-scale aircraft wake vortices. The technique measures the Doppler shift of light scattered from atmospheric particles, and hence infers the line-of-sight flow velocity allowing a picture of vortex flow to be built up. Detection and monitoring of vortices at ranges exceeding a few hundred meters is best carried out using pulsed lidar; in contrast, detailed measurements at short range are better obtained with continuous-wave (CW) lidar. This presentation concentrated on characterization of wake vortices by CW lidar measurements; the work has potential to aid low-vortex wing design, and for quantifying the vortex hazard from existing aircraft. Data will be presented from several trials conducted by DERA/QinetiQ at Heathrow, Toulouse and Munich. Analysis techniques will be outlined for obtaining vortex characteristics such as circulation and trajectory. The influence of atmospheric conditions and local topography on vortex measurements will be discussed.

Harris, M., Vaughan, J. M., Huenecke, K. and Huenecke, C.

"AIRCRAFT WAKE VORTICES: A COMPARISON OF WIND-TUNNEL DATA WITH FIELD TRIAL MEASUREMENTS BY LASER RADAR"

Aerospace Science and Tech., Vol. 4, 2000, pp. 363-370

A method is presented for comparison of measurements on aircraft wake vortices obtained using two very different techniques: 1) five-hole probe measurements on a 1/13.6 (7.35%) scale half-model of an Airbus A321 were made in a wind tunnel, and 2) coherent laser radar (lidar) measurements were made in full-scale field trials at Toulouse Blagnac Airport. The lidar measurements provide line-of-sight tangent velocities across the vortex pair to over half the peak core velocity, whereas the wind tunnel measurements cover the full core region, extending nearly to the mid-point. Measurements from the two systems may thus be compared over the overlap region of the vortex profile. Over this range the measured tangent velocity profiles show good agreement for vortices of comparable age. Vortex disturbance is brought about by atmospheric turbulence, and the effects are evident in the lidar data, leading to significant distortion of older vortices. Some implications of the results are discussed together with points of comparison for the two measurement systems. The complementary character of the information that may be derived from the two techniques is emphasized.

Harris, M., Young, R. I. and Vaughan, J. M.

"MEASUREMENTS OF AIRCRAFT WAKE VORTEX STRUCTURE BY CW COHERENT LASER RADAR"

Tenth Biennial Coherent Laser Radar Technology and Applications Conference, November 1999, pp. 203-206

The laser sensors group at DERA Malvern has a long history of detailed measurements of aircraft wake vortices. The equipment used has recently been upgraded to achieve improved accuracy in determining the core separation. The use of direction-sensing lidar giving the ability to distinguish the sign (direction) of wind velocity allows the acquisition of superior data compared to earlier DERA trials. The increased ability to define the position of the core vortex gives greater accuracy in measurements of the circulation. The gathering of a large database allows the potential to build a comprehensive picture of vortex evolution and decay. The upgraded equipment was deployed on a trial for Airbus Industrie at Toulouse Blagnac during March 1998, with the aim of making measurements of wake turbulence from aircraft on the final approach to the runway. Laser radar has proved a useful tool for examining vortices and hence determining the necessary separation distances between landing aircraft. Laser radar has a further role to play in the negation of vortices. Detailed measurement of the vortex core may allow for the optimization of aircraft wing design to ameliorate vorticity and enhance decay. The possibility of making high-quality measurements has been demonstrated on full-scale aircraft in the real atmosphere. Such measurements are thus complementary to the information provided by wind tunnel studies. However, to achieve optimum and reproducible results, the lidar measurements must be made under stringent atmospheric conditions.

Harris, M., Young, R. I., Kopp, F., Dolfi, A. and Cariou, J.-P.

"WAKE VORTEX DETECTION AND MONITORING"

Aerospace Science and Technology, Vol. 6, Sept. 2002, pp. 325-331

Coherent laser radar (CLR) or lidar is a powerful technique for the detection and study of aircraft wake vortices. The technique measures the Doppler shift of light scattered from atmospheric particles, and hence infers the line-of-sight flow velocity allowing a picture of vortex flow to be built up. Monitoring of vortices at ranges exceeding a few hundred meters is best carried out using pulsed lidar: results of the field trials using the MFLAME system will be presented, including an analysis of the potential for on-board detection. Detailed measurements at short range are better obtained with continuous-wave (CW) lidar, and work will be presented on characterization of design, and for quantifying the vortex hazard from existing aircraft. Finally, the possibility for employing lidar in reduced-scale studies (catapult and wind tunnel) will be discussed.

Harris, M., Young, R. I., Kopp, F., Dolfi, A. and Cariou, J.-P.

"WAKE VORTEX DETECTION AND MONITORING"

3rd ONERA-DLR Aerospace Symposium, June 2001, Paris, pp. S3-3/1-7.

Coherent laser radar (CLR) or lidar is a powerful technique for the detection and study of aircraft wake vortices. The technique measures the Doppler shift of light scattered from atmospheric particles, and hence infers the line-of-sight flow velocity allowing a picture of vortex flow to be built up. Monitoring of vortices at ranges exceeding a few hundred meters is best carried out using pulsed lidar: results of the field trials using the MFLAME system will be presented, including an analysis of the potential for on-board detection. Detailed measurements at short range are better obtained with continuous-wave (CW) lidar, and work will be presented on characterization of wake vortices by CW lidar measurements. These studies have potential to aid low-vortex wing design, and for quantifying the vortex hazard from existing aircraft. Finally, the possibility for employing lidar in reduced-scale studies (catapult and wind tunnel) will be discussed.

Hart, A. and Ukeiley, L.

"TIP VORTEX DEVELOPMENT ON A PITCHING-PLUNGING LOW ASPECT RATIO FLAT PLATE"

AIAA Paper No. 2011-3580, June 2011, Honolulu, Hawaii.

Many natural flyers utilize low-aspect-ratio wings to harness unsteady flow features which enhance their flight characteristics in the low Reynolds number regime. This study investigates the tip vortices' development and interaction with the leading edge (LE) circulation regions on a low-aspect-ratio, flat plate subjected to a pitch-plunge motion. Stereoscopic Particle Image Velocimetry is used to measure the flow field over a flat plate throughout the downstroke of a pitch-plunge kinematic motion with varying phase lags and a pure plunge kinematic motion. Phase averaged velocity fields are calculated along various streamwise locations centered at the tip of the flat plate. The strength of the tip vortex is shown to increase in the streamwise direction, except for when the plate is at a low effective angle of attack. The slope of the tip vortex core separation from the upper surface of wing in the chordwise direction remains relatively constant. The initial displacement of the tip vortex structure is shown to be dependent upon the plunge velocity. Also, it is seen that two different flow mechanisms exist between the tip vortex and LE circulation region based upon their transient development throughout the downstroke. Outward spanwise flow from the LE circulation region exists in the absence of existing, inward spanwise velocity over the wing tip. This occurs for the pure plunge and pitch-plunge kinematic motion with a phase lag of 30 degrees. The outward flow provides added momentum to the tip vortex structure thereby strengthening it downstream.

Hart, D. P.

"CAVITATION AND WAKE STRUCTURE OF UNSTEADY TIP VORTEX FLOWS"

PhD Thesis, December 1992, California Institute of Technology, Pasadena, CA.

Unsteady flows are prevalent in virtually every fluid application yet, because of their intrinsic complexity, few attempts have been made to measure them or explain their behavior. This thesis presents an experimental study of one of the simplest unsteady flow-induced effects, the periodic change in angle of attack of a lifting surface. Of particular interest is the influence this effect has on the

tip vortex structure of a finite aspect ratio hydrofoil and the part it plays in the inception of cavitation. An aspect ratio 2.3 hydrofoil was reflection-plane mounted to the test section floor of the Caltech Low Turbulence Water Tunnel and harmonically oscillated in pitch near its center of pressure. Observations of the growth and collapse of surface and tip vortex cavitation were made along with detailed observations of the interaction of the tip vortex formation with the spanwise wake structure. Measurements of the cavitation inception number for surface cavitation and tip vortex cavitation were made relative to the phase of the hydrofoil and the reduced frequency, k , of oscillation. Studies of the oscillation-induced spanwise trailing vortex structures and the Karman vortex street generated by the boundary layer were made of a two-dimensional hydrofoil. Laser Doppler Velocimetry measurements were taken of the tip vortex velocity profile and the flow at the trailing edge of both the two- and the three-dimensional hydrofoils at reduced frequencies ranging from 0.5 to 2.0. Dynamic changes in bound circulation and shed vorticity in the streamwise and spanwise directions relative to the freestream were calculated from these measurements at three locations along the span of the foil. The results of these measurements are compared to theoretical flow calculations and related to measurements of the cavitation inception number in the tip vortex region of the three-dimensional foil.

Hartman, R. J. and Lewis, H. W.

"WAKE COLLAPSE IN A STRATIFIED FLUID: LINEAR TREATMENT"

J. Fluid Mech., Vol. 51, Part 3, 1972, pp. 613-618

The linear initial-value problem of a partially mixed cylindrical wake in a uniformly stratified fluid is formulated and exact solutions are given for the density and velocity fields inside and just outside the original cylinder. An asymptotic expression for the far-field internal wave radiation is given and the corresponding solutions for a spherical wake geometry are noted. The treatment emphasizes the inadequacy of the usual linear Boussinesq approximation to describe the detailed nature of similar problems, in particular, the fully mixed wake-collapse problem.

Harvey, A.

"THE CREDOS PROJECT: ALIGNMENT OF THE CREDOS CONCEPT WITH THE SESAR PROGRAMME"

D5-4, February 2009.

The CREDOS project aims to demonstrate the feasibility of a departure operation whereby the wake turbulence separations between successive aircraft are temporary suspended under specific (favorable) crosswind conditions. This report considers the alignment of the aims of the CREDOS project with the SESAR target concept and work program.

Harvey, A.

"THE CREDOS PROJECT: PILOT INFORMATION PACKAGE"

D5-6, November.

The CREDOS project aims to demonstrate the feasibility of a departure operation whereby the wake turbulence separations between successive aircraft are temporary suspended under specific (favorable) crosswind conditions. This report considers the alignment of the aims of the CREDOS project with the SESAR target concept and work program.

Harvey, A.

"THE CREDOS PROJECT: ATCO INFORMATION PACKAGE"

D5-5, November 2009.

The CREDOS project aims to demonstrate the feasibility of a departure operation whereby the wake turbulence separations between successive aircraft are temporary suspended under specific (favorable) crosswind conditions. This report considers the alignment of the aims of the CREDOS project with the SESAR target concept and work program.

Harvey, J. K.

"SOME OBSERVATIONS OF THE VORTEX BREAKDOWN PHENOMENON"

J. Fluid Mech., Vol. 14, Part 4, December 1962, pp. 585-592

This paper describes an experiment in which a cylindrical vortex, formed in a long tube, was used to study the 'vortex breakdown' that has been previously reported in investigations of the flow over slender delta wings. By varying the amount of swirl that was imparted to the fluid before it entered the tube, it was found that the breakdown was the intermediate stage between the two basic types of rotating flows, that is, those that do and those that do not exhibit axial velocity reversal. In addition, it was shown that an unusual flow pattern was established after the breakdown and that certain features of this pointed to it being a 'critical' phenomenon. The tests were concluded by measuring the swirl angle distribution a short distance ahead of the breakdown and comparing these results with the prediction of Squire's theory.

Harvey, J. K. and Fackrell, J. E.

"OBSERVATION OF A MECHANISM CAUSING A TRAILING VORTEX TO BREAK UP"

IC-AERO-70-08, December 1970, Imperial College, London, England.

Simple flow visualization experiments have been performed to identify a new form of vortex breakdown which is characterized by the disturbance appearing somewhere near the edge of the core and not on the vortex center line. There is a marked similarity between the disc observed and those seen in condensation trails. In the experiments a towing tank was used which enabled the vortices to

be studied within a frame of reference which was stationary with respect to the undisturbed fluid and so their total history could be observed.

Harvey, J. K. and Perry, F. J.

"FLOWFIELD PRODUCED BY TRAILING VORTICES IN THE VICINITY OF THE GROUND"

AIAA Journal, Vol. 9, No. 8, August 1971, pp. 1659-1660

Vortices have been noted to rise again after having descended close to the ground. To attempt to explain this phenomenon, a series of total-head surveys in planes across the flow were made in a wind tunnel with a single trailing vortex passing over a moving floor simulating the ground boundary condition. The vortex induces a cross flow on the floor with an attendant suction peak beneath the core. Consequently, the boundary layer resulting from the cross flow must negotiate an adverse pressure gradient once it has passed under the vortex. When the vortex is sufficiently near the ground, the pressure gradient is strong enough for separation to occur, and a bubble forms containing vorticity of opposite sense to the main vortex. Progressing downstream, the bubble detaches from the floor as a secondary vortex fed by a vortex sheet from the separation point. The subsequent motion of the two vortices is complicated but the secondary vortex can induce an upward velocity on the main vortex.

Harvey, J. K. and Steiner, T. R.

"DISPERSION IN THE WAKE OF AIRCRAFT: AN INVESTIGATION OF THE EFFECTS OF A GROUND PLANE ON TRAILING VORTICES: LITERATURE SURVEY"

IC-AERO-REP-86-04, June 1986, Imperial College of Science and Technology, London, England

Physical processes of trailing vortices are discussed, and the complexities and subtleties of aircraft wake flow are explored. A literature survey detects little work of direct relevance to the problem of dispersion of aircraft wake material, especially near the ground. However, problems and likely areas of useful research are identified.

Hasegawa, H., Matsuuchi, K. and Yamakami, J.

"THE MECHANISM OF ACTIVE BOUNDARY LAYER CONTROL USING VORTEX GENERATOR JETS"

ICAS-98-3.4.3, September 1998, Melbourne, Australia.

The vortex generator jet method is an active control of flow separation that can provide a time-varying control action to optimize performance under a wide range of flow conditions. Pitched and skewed jets issue into a free stream and the interaction between the jets and the free stream generates longitudinal (streamwise) vortices. The mechanism for suppressing flow separation was studied experimentally by making a comparison between two effects of steady and pulsed jets on generating longitudinal vortices. The suppression of flow separation is accomplished by the secondary flow of longitudinal vortices which transport high momentum fluid of the free stream to the lower wall.

However, if the vortex moves away from the lower wall, a counter-rotating vortex of nearly equal strength is induced, and thus an upwash region is produced by the effect of a vortex pair. The upwash makes ineffective the secondary flow toward the lower wall. Consequently, the boundary layer thickness is strongly distorted and is not uniform in the spanwise direction because streamwise velocity decreases near the outer edge of the boundary layer. Pulsed jets enhance the mixing process in comparison with steady jets and indicate effective separation control for the purpose of keeping the vortex near the lower wall.

Hashemabadi, H. K.

"AERODYNAMIC ANALYSIS OF HELICOPTER ROTOR USING FREE WAKE VORTEX LATTICE METHOD"

Journal of Faculty Engineering, , Vol. 40, Jan. 2007, pp. 895-906.

The accurate computation of helicopter rotor flow leads to an accurate calculation of rotor blade aerodynamic loads. The flow field around a rotor is difficult to model due to the presence of vortical wake. The complexity of the rotor flow field results from the effects of strong vortical wake and primary vortical structures that are convected away from the rotor disk at relatively low speeds. In the present work, a free wake vortex lattice method is used to accurately predict the vortical wake and blade loading of an isolated rotor in hover. In the vortex lattice method, the blades are modeled as flat plates with zero thickness and ring vortices are distributed on the surface of each blade. When the blades rotate, the vortices are shed into the wake and freely moved with a velocity induced by the effects of the vortices located on the blades and in the wake. The wake can freely deform over time to take its natural shape. The distribution of lift can be computed from the strength of each vortex on the blade. The aerodynamic analysis of a wing in oscillating motion for different reduced frequencies is performed to show the accuracy of the free wake vortex lattice method for unsteady calculations. Then, the aerodynamic calculations are performed for a hovering helicopter rotor for two operating conditions of subsonic and transonic tip Mach numbers (0.44, 0.88). To accurately compute the compressible flow case, the Prandtl-Glauert correction is applied to the Biot-Savart Law. The present calculations based on the free wake vortex lattice method are compared with available theoretical and experimental results. The effects of number of panels, vortex core radius, and computational time step on the aerodynamic results and wake structure are also studied. Finally, the capability of the free wake vortex lattice method for aerodynamic analysis of the rotor blades with twist is demonstrated.

Haskin, M.

"DEFINING VALID GEOMETRIC ALTITUDE ROUND 2: GEOMETRIC ALTITUDE VALIDITY FOR DO-317C"

DO-317C, RTCA, June 2019, RTCA, Washington, DC.

This working paper addresses an action from WG4 Meeting 314 to define valid geometric altitude . It also addresses actions taken from WG4 Teleconference on April 17th. The highlighted portions are what is being proposed to change.

Hastings, Jr., E. C. and Champine, R. A.

"RESULTS OF FULL-SCALE VORTEX ATTENUATION FLIGHT EXPERIMENTS"

Proceedings of the Fifth Annual Symposium of the Society of Flight Test Engineers, SFTE, 1974, pp. 4/26-4/46

Flight tests have been conducted to evaluate the effectiveness of a wing-tip vortex attenuating device called a spline. Vortex penetrations were made with a PA-28 behind a C-54 aircraft with and without wing-tip splines attached and the resultant rolling acceleration was measured and related to the roll acceleration capability of the PA-28.

Hastings, Jr., E. C. and Keyser, Jr., G. L.

"SIMULATED VORTEX ENCOUNTERS BY A TWIN-ENGINE COMMERCIAL TRANSPORT AIRCRAFT DURING FINAL APPROACH"

SAE Paper No. 800775, Cincinnati, OH, May 1980

Piloted simulations of encounters with vortices of various ages and degrees of attenuation were performed with the Visual Motion Simulator. In the simulations, a twin-engine, commercial transport on final approach encountered the modeled vortices of a four-engine, wide-body, commercial transport. The data in this report show the effect of vortex age and ground effect on the severity of the initial upset, as well as the effect of the vortex encounters on the landing capability.

Hastings, Jr., E. C. and Keyser, Jr., G. L.

"SIMULATOR STUDY OF VORTEX ENCOUNTERS BY A TWIN-ENGINE, COMMERCIAL, JET TRANSPORT AIRPLANE"

NASA TP-1966, February 1982, Langley Research Center, Hampton, V.

An investigation of vortex-induced upset and recovery characteristics was conducted by using a simulated twin-engine, commercial, jet transport airplane with fixed controls and with a conventional manual-control system. The piloted simulations were performed with the Langley Visual/Motion Simulator. Wake vortex encounters were simulated with the airplane in the final-approach configuration at altitudes between 76.2 m and 30.5 m. The investigation consisted of parametric studies of the effects of the lateral and vertical locations of the vortex center, vortex aging in and out of ground effect, approach speed of the simulated following airplane, lift coefficient of the vortex-generating airplane, and vortex attenuation by using the flight spoilers of the vortex-generating airplane. In addition, altitude-dependent bank angle and flight-path excursion criteria were used to evaluate the acceptability of the vortex-induced upsets.

Hastings, Jr., E. C., Holbrook, G. T. and Keyser, Jr., G. L.

"PRELIMINARY RESULTS OF SIMULATED VORTEX ENCOUNTERS BY A TWIN-ENGINE, COMMERCIAL AIRCRAFT DURING FINAL LANDING APPROACH"

NASA TM-81782, May 1980, Langley Research Center, Hampton, VA.

Piloted simulations of encounters with vortices of various ages and degrees of attenuation have been performed with the Visual Motion Simulator at the Langley Research Center. In the simulations, a twin-engine, commercial transport on final approach, encountered the modeled vortices of a four-engine, wide-body, commercial transport. Unattenuated vortices (in-and out-of-ground effect) and vortices attenuated by the spoilers of the generating aircraft were used in the simulations. The results show that the upset severity due to encounters with unattenuated vortices out-of-ground effect, decreased very little with vortex aging. The presence of ground effect, or the utilization of spoiler attenuation, had little effect on the upset severity for vortices near 45 seconds of age. The upset severity of the ground effect and 15-deg. spoiler vortex encounters however, diminished more rapidly as the vortices aged.

Hastings, Jr., E. C., Patterson, Jr., J. C., Shanks, R. E., Champine, R. A., Copeland, W. L., Latham W. and Young, D. C.

"DEVELOPMENT AND FLIGHT TESTS OF VORTEX ATTENUATING SPLINES"

NASA TN D-8083, November 1975, Langley Research Center, Hampton, VA

The report describes some of the ground test and full-scale flight test conducted by the Langley Research Center during development of the vortex-attenuating spline. The flight tests were conducted using a vortex generating aircraft with and without splines; a second aircraft was used to probe the vortices generated in both cases. The results showed that splines significantly reduced the vortex effects, but resulted in some noise and climb performance penalties on the generating aircraft.

Hastings, Jr., E. C., Shanks, R. E., Champine, R. A., Copeland, W. L., Latham, W. and Young, D. C.

"PRELIMINARY RESULTS OF FLIGHT TESTS OF VORTEX ATTENUATING SPLINES"

NASA TMX-71928, March 1974, NASA Langley Research Center, Hampton, VA

Flight tests have been conducted to evaluate the effectiveness of a wingtip vortex attenuating device, referred to as a spline. Vortex penetrations were made with a PA-28 behind a C-54 aircraft with and without wingtip splines attached and the resultant rolling acceleration was measured and related to the roll acceleration capability of the PA-28. Preliminary results indicate that the splines led to a significant reduction in the vortex induced roll acceleration experienced by the PA-28 probe aircraft.

Haussling, H. J.

"COMPUTATIONAL EXPERIMENTS ON THE TRACKING OF VORTICES; FINAL REPORT"

CARDIVNSWC TR-95/021, August 1995, Naval Surface Warfare Center, Carderock Division, Bethesda, MD

A general-purpose viscous flow code, DTNS3D, has been used to compute the strength and trajectories of an isolated vortex and a vortex pair. Analytic solutions and previous computations are used to judge the accuracy of the three-dimensional steady state results. It is possible to track, quite accurately, the decay and translation of these vortex structures. A byproduct of this study is some information on the limitations of the unsteady crossflow analogy and on the effect of axial velocity variations on vortex trajectories.

Haverdings, H.

"WAVENDA ALGORITHM AND PERFORMANCE TESTS"

CREDOS Report D2-2, February 2009, NLR, Amsterdam, The Netherlands.

A Wake Vortex Detection Algorithm (WAVENDA) was adapted for the detection of aircraft Wake Vortex Encounters (WVE) using Flight Data Recording (FDR) data. The algorithm is an improved, adapted version of an already existing algorithm NLR-VORTEX, developed by NLR, but has been made suitable to also process take-off data, and it has reduced false alert rate. Use has been made of discriminant analysis techniques to derive classification functions on Wake Vortex Encounter FDR data provided. This updated document (D2-2) gives both a detailed description of the algorithm as well as results on a performance test and an initial validation using simulated landing approach and take-off data on flights through a Wake Vortex as well as of an actual Wake Vortex Encounter that has occurred.

Haverdings, H.

"THE NLR-VORTEX ALGORITHM: DETECTION OF WAKE VORTEX ENCOUNTERS FROM FLIGHT DATA RECORDER DATA"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

In 1999 NLR began the development of an algorithm that allows wake vortex encounters to be detected from processing Flight Data Recorder (FDR) data. Initially, in cooperation with the National Air Traffic Services Ltd, from 1999 to 2000 the first part of the algorithm, the so-called WINDGRAD algorithm, was developed, which computes wind gradients from available inertial and aerodynamic data. Sophisticated data processing takes place to derive these quantities from basic FDR data. Among these are angle of attack calibrations performed on the data, computation of the sideslip angle from lateral accelerations, the application of Kalman filtering and smoothing to determine the inertial path (in 3D), and computation of a pseudo-vorticity, i.e. the rotation in the airflow through which the aircraft flew. For this process to be possible, estimates of the aircraft's stability derivatives were obtained from the same data set. Although the estimation process worked well, some values of derivatives are

questionable. In the S-wake project NLR developed the second part of the algorithm, the so-called VDC algorithm Vortex Detection and Classification. From the available wind gradients and other parameters (as a pre-cursor to the vorticity data) an initial detection logic was devised, assuming the data has a normal distribution. In this case signal-to-noise ratios were computed for several variables that were assumed to play a role in detecting the true occurrence of an encounter. Later NLR developed an alternative algorithm based on the use of the vorticity data. The NLR-VORTEX algorithm was applied to the Heathrow database built up in the S-Wake project. The final algorithm as it stands per 2002 works well and gave a wake vortex encounter alert for all those cases where, by visual inspection and through pilot reports, a valid encounter occurred in the Heathrow database. However, the NLR-VORTEX algorithm was sensitive to false alarms, in that it indicated more events to have occurred than really was the case. This relatively high false alarm rate was primarily due to lower-than-desired data quality, in terms of data dropouts, sampling rate, etc., and due to the use of non-validated values for aircraft's stability derivatives. This is evidenced by the fact that for the experimental test aircraft good results were obtained; from this aircraft all required data were known well. Future efforts will therefore focus on reducing the false alarm rate by introducing more filtering at the proper points in the algorithm as well as different kinds of standardization, and by replacing estimates of stability derivatives by values given by the airplane manufacturer (preferably per configuration, i.e. a function of flap setting, Mach, etc.).

Haverdings, H. and Chan, P. W.

"QUICK ACCESS RECORDER (QAR) DATA ANALYSIS SOFTWARE FOR STUDIES OF WINDSHEAR, TURBULENCE AND WAKE VORTEX"

NLR-TP-2010-435, April 2012, National Aerospace Laboratory, Amsterdam, The Netherlands.

For analysis of low-level windshear and turbulence events at the Hong Kong International Airport (HKIA), besides pilot reports routinely received from Air Traffic Control, Quick Access Recorder (QAR) data are obtained from the local airlines by the Hong Kong Observatory (HKO). Instead of using directly the wind data recorded on the aircraft by the flight management system, there has been a collaborative study between HKO and the National Aerospace Laboratory (NLR) in The Netherlands to develop a QAR data analysis software to calculate the meteorological quantities, such as the three components of the wind, windshear hazard factor, and turbulence intensity parameters, taking into account the aircraft's aerodynamic factors (e.g. sideslip angle, angle-of-attack). This paper describes the main features of the calculation software, named WINDSTURB, and illustrates its application to windshear and turbulence studies through selected cases at HKIA.

Haverdings, H. and Chan, P. W.

"QUICK ACCESS RECORDER (QAR) DATA ANALYSIS SOFTWARE FOR WINDSHEAR AND TURBULENCE STUDIES"

AIAA Paper 2009-3871, June 2009, San Antonio, Texas.

For analysis of low-level windshear and turbulence events at the Hong Kong International Airport (HKIA), besides pilot reports routinely received from Air Traffic Control, Quick Access Recorder (QAR) data are obtained from the local airlines by the Hong Kong Observatory (HKO). Instead of using directly the wind data recorded on the aircraft by the flight management system (FMS), there has been a collaborative study between HKO and the National Aerospace Laboratory (NLR) in The Netherlands to develop a QAR data analysis software to calculate the meteorological quantities, such as the three components of the wind, windshear hazard factor and turbulence intensity parameters, taking into account the aircraft's aerodynamic factors (e.g. sideslip angle, angle-of-attack). This paper describes the main features of the calculation software, named WINDSTURB, and illustrates its application to windshear and turbulence studies through selected cases at HKIA.

Haverkamp, S., Neuwerth, G. and Jacob, D.

"ACTIVE AND PASSIVE VORTEX WAKE MITIGATION USING CONTROL SURFACES"

Aerospace Science and Tech., Vol. 9, 2005, pp. 5-18

Aircraft trailing vortices constitute a hazard to following aircraft and are therefore one of the main concerns for airport capacity constraints. At the Institute of Aerospace Engineering experiments on wake vortices are conducted in a towing tank using particle image velocimetry. The motivation behind the presented investigations is the alleviation of the rolling moment induced on following aircraft using control surfaces of the preceding aircraft. An unstable vortex system is generated using control surfaces. The instabilities lead to a mitigation of the vortex system. A variety of outboard flaps are used in preliminary studies to estimate the sizing and deflection of ailerons that lead to a vortex system with strong cooperative instabilities and thus to an alleviation of the rolling moment induced on following aircraft. In subsequent experiments a rectangular wing is equipped with preset ailerons, producing an unstable vortex system in its wake. The instabilities are excited by oscillating the ailerons. Each half-wing is equipped with two adjacent ailerons that oscillate in counter-phase in order to minimise fluctuations of the lift coefficient.

Haverkamp, S., Neuwerth, G. and Jacob, D.

"ACTIVE CONTROL OF AIRCRAFT VORTEX WAKES BY MEANS OF PRESET AILERONS"

AIAA Paper No. 2003-6823, Denver, CO, Nov. 2003

Aircraft trailing vortices constitute a hazard to following aircraft, and are therefore one of the main concerns for airport capacity constraints. At the Institute of Aerospace Engineering, experiments on wake vortices up to 50 spans behind the model of a rectangular wing are conducted in a towing tank. The motivation behind the presented experiments is the alleviation of the rolling moment induced on following aircraft by constructive means at wings and flaps of the preceding aircraft. It is shown that within 50 spans behind the wing a reduction of the induced rolling moment by approximately 50% can be achieved by an appropriate aileron preset alone. This is due to an increase of the effective vortex

size resulting from the counter-rotating vortex pairs produced by the ailerons. Oscillating the ailerons induces a sinusoidal perturbation of the vortices and accelerates the onset of rapid decay.

Haverkamp, S., Neuwerth, G. and Jacob, D.

"EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF WING GEOMETRY ON ITS WAKE IN A TOWING TANK"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

At the Institute of Aerospace Engineering experiments on wake vortices in the near far field up to 60 spans behind the model are conducted in a towing tank. The motivation behind the presented experiments is the alleviation of the induced rolling moment posed to following aircraft by constructive means at wings and flaps of the preceding aircraft. The influence of the geometry of outboard flap extensions on the wake of a rectangular wing is investigated. Towing tank experiments using Particle Image Velocimetry are conducted, and the induced rolling moment is calculated from the experimentally determined downwash. The idea is to trigger instabilities in the vortex wake by inserting counter-rotating secondary vortices. These secondary vortices are generated using outboard flap extensions of different shape. A significant reduction of the induced rolling moment by more than 50% can be achieved by inserting counter-rotating vortices into the wake.

Haverkamp, S., Neuwerth, G. and Jacob, D.

"STUDIES ON THE INFLUENCE OF OUTBOARD FLAPS ON THE VORTEX WAKE OF A RECTANGULAR WING"

Aerospace Science and Technology, Vol. 7, 2003, pp. 331-339

Aircraft trailing vortices constitute a hazard to following aircraft, and are therefore one of the main concerns for airport capacity constraints. At the Institute of Aerospace Engineering (ILR) experiments on wake vortices up to 60 spans behind the model of a rectangular wing are conducted in a towing tank. The motivation behind the presented experiments is the alleviation of the rolling moment induced on following aircraft by constructive means at wings and flaps of the preceding aircraft. Following the approach of Ortega et al., the influence of the geometry of outboard flap extensions on the wake of a rectangular wing is investigated. Towing tank experiments using Particle Image Velocimetry are conducted, and the induced rolling moment is calculated from the experimentally determined downwash. In addition, a stability analysis is performed for the experimentally investigated four-vortex configurations utilizing the linearized Biot-Savart law as proposed by Crow. It is assumed that the vortex system attunes to the most unstable eigenform. The theoretical results help giving an interpretation of the experimental data. It is shown that a significant reduction of the induced rolling moment by more than 50% can be achieved using outboard flap extensions. This is due to an increase of the effective vortex size resulting from the counter-rotating vortex pairs produced by the flaps.

Hawkes, J. W.

"A SIMPLE MODEL FOR THE VORTEX BREAKDOWN PHENOMENON"

M.S. Thesis, August 1969, Mass. Institute of Technology, Cambridge, MA

Previous experimental and theoretical investigations of vortex breakdown are reviewed. Considering past experimental results, a new model for the vortex breakdown is proposed. It is modelled as a transition from an upstream uniform vortex core to a downstream flow in which there exists a stagnant bubble on the axis. The conservation equations are applied across this transition under the constraint that the pressure jump in the breakdown be a maximum. Model results indicate that a pressure increase in the stagnant bubble of about 75% of the initial maximum swirl dynamic head is to be expected at swirl ratios comparable to those observed experimentally to involve a breakdown. Radii predicted for the breakdown bubbles are compared on a limited basis with experiments and reasonable agreement obtained.

Hay, G. C.

"FAA R&D OBJECTIVES REGARDING WAKE TURBULENCE"

FAA Symposium on Turbulence, Federal Aviation Administration, Washington, DC, March 1971, p. 26

The FAA breaks the wake vortices program into three parts, each being examined concurrently. One part is to eliminate or minimize the problem at its sources; NASA has been asked to pursue this effort. Second, real time detection and measurement concepts using present day technology is being examined; this includes system designs, the feasibility of a predictive system, and the identification of hazardous conditions. Third, in concert with the National Airspace System users, current operational procedures need to be updated.

Hayashi, H., Kodama, Y., Fukano, T. and Ikeda, M.

"RELATION BETWEEN WAKE VORTEX FORMATION AND DISCRETE FREQUENCY NOISE"

In: Separated and Complex Flows - 1995; Proceedings of the ASME/JSME Fluids Engineering and Laser Anemometry Conference and Exhibition, Hilton Head, SC, August 1995, pp. 107-114

The discrete frequency noise (DFN) generated by the wake vortex have been investigated for symmetrical NACA airfoils of three different thicknesses submerged in a uniform main flow. It was clarified that the airfoil thickness have influence on the flow characteristics of the near wake and the DFN in the case of low attack angles. The position of rolling up of the wake vortex was far from the trailing edge, the vortices did not have a strong effect on the flow around the airfoil. However, when rolling up took place in the vicinity of the airfoil, the interaction between the wake vortices and the surface flow was strong. The shear layers near the trailing edge were swinging with rolling up of the wake vortex and the DFN was generated by the pressure fluctuation with this swinging shear layer.

Hayashi, H., Sasaki, S., Kodama, Y. and Fukano, T.

"STUDY OF 3-DIMENSIONAL COHERENT STRUCTURE OF WAKE VORTICES AND AEROACOUSTIC SOURCE"

AIAA Paper No. 2000-1974, Lahaina, HI, June 2000

The coherent structure of the wake of a body was investigated to clarify the mechanism of aeolian tone from an isolated blade immersed in a uniform flow field. In the Reynolds number transition region, the sound power of the aeolian tone from an isolated blade is proportional to the sixth power of the main flow velocity; it is then well known that the sound is closely related to the wake characteristics. It was found that the Karman vortices shed from a symmetrical NACA blade have a multiple cell structure, whose phase is shifted at each span position. The authors propose a new correlation coefficient which considers the coherence function and the phase difference, and which was used to estimate the statistical length within which a pair of Karman vortices is shed. In an experiment on an isolated blade with bluff trailing edge, it was found that the span direction velocity fluctuation is an important parameter for relaxing the regulation of the wake vortex, and an empirical relationship between the correlation length and the velocity fluctuation is proposed. These phenomena were also verified by a 3-D numerical simulation. Lastly, prediction of the discrete frequency noise level by using this correlation length indicates ± 3 dB accuracy.

Hayes, D., Lone, M., Whidborne, J. F. and Coetzee, E.

"EVALUATING THE RATIONALE FOR FOLDING WING TIPS COMPARING THE EXERGY AND BREGUET APPROACHES"

AIAA Paper 2017-0464, January 2017, Grapevine, TX.

The design and development processes for future aircraft aims to address the environmental and efficiency challenges needed to facilitate the engineering of concepts that are far more integrated and require a multidisciplinary approach. This study investigates the benefit of incorporating span extension wing tips onto future aircraft configurations as a method of providing improved aerodynamic efficiency, whilst allowing the extension to fold on the ground to meet airport gate size constraints. Although the actuated wing tips are not studied in detail, the focus of this study is to compare two different methods of analysis that can be used to identify the benefit and limitations of adding such devices. The two methods considered are a quasi-steady implicit energy analysis based on the Breguet Range Equation and an explicit energy analysis based on the first and second laws of thermodynamics known as Exergy Analysis. It has been found that both methods provide agreeable results and have individual merits. The Breguet Range Equation can provide quick results in early design, whilst the Energy Analysis has been found to be far more extensive and allows the complete dynamic behavior of the aircraft to be assessed through a single metric. Hence, allowing comparison of losses from multiple subsystems.

He, A. and Zheng, Z. C.

"AERODYNAMIC SIMULATION OF WAKE ENCOUNTER FOR AIRCRAFT CLOSE FORMATION OPERATIONS"

AIAA Paper 2015-3319, June 2015, Dallas, TX.

In this study, the rolling moment coefficient of a following unmanned aerial vehicle (UAV) induced by wake vortices from a leading UAV is analyzed and studied. Numerical simulation results are compared to the results from an analytical vortex lattice method. Then a complete UAV mesh is built and used to calculate the influence by a pair of wake vortices created by the leading UAV in real flight scenario. The paper provides an estimate of the vortex roll hazard assessment for the following UAV in close formation operations.

He, A., Tian, P., Zheng, Z. C., Chao, H. and Gu, Y.

"A STUDY ON UAS WAKE TURBULENCE ENCOUNTER USING COUPLED AERODYNAMICS AND FLIGHT DYNAMICS SIMULATION"

AIAA Paper 2016-3439, June 2016, Washington, DC.

In this paper, a new UAS wake encounter simulation platform with coupled modeling of aerodynamics and flight dynamics is presented. Two wake encounter scenarios with different lateral encounter angles are investigated as the examples. The influence of wake encounters on the follower aircraft during the cutting through is simulated and further discussed. In the 90-degree lateral encounter case, the unmanned aircraft can still go back to steady state after experiencing vortex wake disturbances without any controller compensation. However, vortex wakes generate observable rolling for the follower UAV undergoing a 30-degree lateral encountering angle. Results show that the wake encounter can cause significant influences to the follower aircraft.

He, C. and Zhao, J.

"MODELING ROTOR WAKE DYNAMICS WITH VISCOUS VORTEX PARTICLE METHOD"

AIAA Paper No. 2008-339, Reno, NV, January 2008

Rotor induced flow modeling and prediction has been one of the central issues for rotorcraft performance, control, and stability, and loads and vibration analysis for decades. Traditional singularity methods used in most of current comprehensive rotorcraft analysis codes are limited by the potential flow assumption and thus must rely on empirical formulation (e.g., vortex core size, etc.) for the solution. This paper discusses the development of a viscous vortex particle model for modeling the complicated rotor wake vorticity transportation and diffusion. Instead of solving the viscous vorticity equations through numerical discretization over the flow field grid, the vortex particle method addresses the solution via Lagrangian formulation where there is no artificial numerical dissipation involved. The Lagrangian approach also allows the application of hierarchical TreeCode and Fast Multipole Method that can dramatically improve the computational efficiency for the vortex particle method for practical and comprehensive rotorcraft analysis.

He, C. and Zhao, J.

"MODELING ROTOR WAKE DYNAMICS WITH VISCOUS VORTEX PARTICLE METHOD"

AIAA Journal, Vol. 47, No. 4, April 2009, pp. 902-915.

Rotor-induced-flow modeling and prediction has been one of the central issues for rotorcraft performance, control, stability, loads, and vibration analysis for decades. Traditional singularity-based methods used in most current comprehensive rotorcraft analysis codes are limited by the potential flow assumption and thus must rely on empirical formulations (e.g., vortex decay factor, vortex core size, etc.) to reach a solution. This paper discusses the development and validation of a viscous vortex particle model for modeling the complicated rotor wake vorticity transportation and diffusion. Instead of solving the viscous vorticity equations through numerical discretization over the flow field grid, the vortex particle method addresses the solution through a Lagrangian formulation in which there is no artificial numerical dissipation involved. The Lagrangian approach also allows the application of the hierarchical TreeCode and the fast multipole method. These methods can dramatically improve the computational efficiency of the viscous vortex particle simulation, which enables it to be used for practical and comprehensive rotorcraft analysis.

He, W., Niu, Z.-G., Pan, B. and Lin, Q.

"STUDY ON EXPERIMENTS FOR SUPPRESSING WINGTIP VORTICES WITH PLASMA"

Engineering Mechanics, Vol. 30, No. 5, May 2013, pp. 277-281.

The wind tunnel experiment on suppressing wingtip vortices (WTV) through adding energy with DBD plasma has been conducted in the paper. The WTV flow field of a swept wing has been visualized by PIV and the aerodynamic forces of a rectangular wing have been measured, in the condition of using three different kinds of plasma actuators respectively. The results show that the WTV may be suppressed and the separation on the upper wingtip surface may be delayed because the energy of the vortex induced by the plasma (VIP) is added into the flow field, which increases the lift and the ratio of lift to drag at a small angle of attack (AOA) effectively. Even at large AOA, the effect of plasma still appears. The effects are related to the structures of the plasma actuators. It can obtain better results to suppress the WTV through optimizing the design of the plasma actuators and choosing the appropriate placement to install the actuators on wingtip surface. [In Chinese.]

He, X. and Herring, J.

"TURBULENCE DISSIPATION PROCESSES OF 2-D AND 3-D VORTICES IN NUMERICAL SIMULATIONS"

AIAA Paper No. 1989-0610, Reno, NV, January 1989

Using the spectral method, the three-dimensional time-dependent Navier-Stokes equations were solved for various initial vortex structures. The significant difference in lifetimes between the three-dimensional and the two-dimensional vortices indicates that the instability of two-dimensional flow is not enough to explain the turbulence development process. Analysis shows that (1) the transfer of kinetic energy from the large vortex to the smaller ones is active in the braid region of the large vortex, and (2) the transfer is mainly through the interaction with neighboring vortex sectors which have different orientation in space. This mechanism is supported by experimental observations.

Heaslet, M. A. and Lomax, H.

"THE CALCULATION OF DOWNWASH BEHIND SUPERSONIC WINGS WITH AN APPLICATION TO TRIANGULAR PLAN FORMS"

NACA Technical Note No. 1620, June 1948, Ames Aeronautical Lab., Moffett Field, CA.

A method is developed consistent with the assumptions of small perturbation theory, which provides a means of determining the downwash behind a wing in supersonic flow for a known load distribution. The analysis is based upon the use of supersonic doublets which are distributed over the plan form and wake of the wing in a manner determined from the wing loading. The first application of the method proves the equivalence in subsonic and supersonic flow of the downwash at infinity corresponding to a given load distribution. The principal application in this report is concerned with the downwash behind a triangular wing with leading edges swept back of the Mach cone from the vertex. A complete solution is given along the center line of the wake and an approximation provided for points in the vicinity of this line.

Heaton, C. J.

"OPTIMAL GROWTH OF THE BATCHELOR VORTEX VISCOUS MODES"

J. Fluid Mech., Vol. 592, 2007, pp. 495-505

We present calculations of optimal linear growth in the Batchelor (or q) vortex. The level of transient growth is used to quantify the effect of the viscous center modes found at large Reynolds number and large swirl. The viscous modes compete with inviscid-type transients, which are seen to provide faster growth at short times. Following a smooth transition, the viscous modes emerge as dominant in a different regime at later times. A comparison is drawn with two-dimensional shear flows, such as boundary layers, in which weak instability modes (Tollmien-Schlichting waves) also compete with inviscid transients (streamwise streaks). We find the competition to be more evenly balanced in the Batchelor vortex, because the inviscid transients are damped faster in a swirling jet than a two-dimensional shear flow, so that despite their weak growth rates the viscous modes may be relevant in some situations.

Heaton, C. J. and Peake, N.

"TRANSIENT GROWTH IN VORTICES WITH AXIAL FLOW"

J. Fluid Mech., Vol. 587, 2007, pp. 271-301

We investigate transient growth in high-Reynolds-number vortices with axial flow. Many cases of vortex instability are not fully explained by strong exponential instability modes, and transient growth could offer an alternative route to breakdown in such cases. Strong transient growth is found, in agreement with previous studies. We first discuss the problem by reference to ducted vortices which

model aeroengine flow. The transient growth is inviscid in character, and in this paper, we specifically interpret it as an effect of the inviscid continuous spectrum. The relevant inviscid theory explains new scalings which we find for the transient growth, which are generalizations of the quadratic scaling seen previously in two-dimensional flows and non-swirling pipe flows. We then turn to a second case, of interest for vortex breakdown, the Batchelor vortex, and present calculations of the transient growth. Large growth is possible, especially for the helical modes (with azimuthal wavenumber). The general trends are complicated by several issues, including a long-wavelength effect and a resonance effect, both of which were recently discovered for a vortex without axial flow and are found here to be present in the Batchelor vortex also. Overall, the results suggest that strong transient effects are present in the moderate- to high-swirl regime of practical interest. For axisymmetric and higher modes, however, transient effects are not found to be significant.

Heaton, C. J., Nichols, J. W. and Schmid, P. J.

"GLOBAL LINEAR STABILITY OF THE NON-PARALLEL BATCHELOR VORTEX"

Journal of Fluid Mechanics, Vol. 629, 2009, pp. 139-160.

Linear stability of the non-parallel Batchelor vortex is studied using global modes. This family of swirling wakes and jets has been extensively studied under the parallel-flow approximation, and in this paper we extend to more realistic non-parallel base flows. Our base flow is obtained as an exact steady solution of the Navier-Stokes equations by direct numerical simulation (with imposed axisymmetry to damp all instabilities). Global stability modes are computed by numerical simulation of the linearized equations, using the implicitly restarted Arnoldi method, and we discuss fully the numerical and convergence issues encountered. Emphasis is placed on exploring the general structure of the global spectrum, and in particular the correspondence between global modes and local absolute modes which is anticipated by weakly non-parallel asymptotic theory. We believe that our computed global modes for a weakly non-parallel vortex are the first to display this correspondence with local absolute modes. Superpositions of global modes are also studied, allowing an investigation of the amplifier dynamics of this unstable flow. For an illustrative case we find global non-modal transient growth via a convective mechanism. Generally, amplifier dynamics, via convective growth, are prevalent over short time intervals, and resonator dynamics, via global mode growth, become prevalent at later times.

Hecht, A. M., Bilanin, A. J. and Hirsh, J. E.

"TURBULENT TRAILING VORTICES IN STRATIFIED FLUIDS"

AIAA Journal, Vol. 19, No. 6, June 1981, pp. 691-698

The effects of stable atmospheric-density stratification, vortex core size, and turbulent scale on the descent of aircraft-trailing vortices are investigated using numerical solutions of a second-order closure turbulent model. A B-747 vortex descent is simulated numerically and compared to reported measurements of descent distance, velocity, and circulation profiles. It is concluded that the pair was halted in its descent by a diffuse region of countersign vorticity primarily outboard and above the

vortex cores. It is shown that the core size and turbulent macroscale have significant effects on vortex behavior through their influence on turbulence production, diffusion, and dissipation.

Hecht, A. M., Bilanin, A. J., Hirsh, J. E. and Snedeker, R. S.

"INVESTIGATION OF STABLE ATMOSPHERIC STRATIFICATION EFFECT ON THE DYNAMICS OF DESCENDING VORTEX PAIRS"

FAA-RD-79-4, February 1979, Aeronautical Research Assoc. of Princeton, Princeton, NJ

The physics of vortex flows in stratified fluids is studied with the objective of determining the influence of stable stratification on the descent of aircraft vortex pairs. Vortex rings descending into linear and discontinuous density stratifications are investigated experimentally and simulated numerically. The computer code used for this is based on a second-order closure turbulence model of the Reynolds stress equations in axisymmetric coordinates. Verification of the code is provided by the agreement found between the measured and calculated results. The two-dimensional version of the code is then used to simulate a measured Boeing-747 vortex descending in stable stratification. The strength and tightness of the measured vortex cores have necessitated development of a new method of numerically calculating strong vortex flows. The comparison of measured with calculated descent velocity, descent distance, swirl velocity, and circulation in the vortex agree. It is concluded that turbulence effects must be accounted for in the study of aircraft vortex behavior. It is found that unalleviated vortices remain strong during descent, that the vortices stop descending due to a diffuse region of countersign vorticity outboard and above the cores, and that core separation does not primarily control descent.

Hecht, A. M., Bilanin, A. J., Hirsh, J. E. and Snedeker, R. S.

"TURBULENT VORTICES IN STRATIFIED FLUIDS"

AIAA Journal, Vol. 18, No. 7, July 1980, pp. 738-746

The effects of density stratification and turbulence on the behavior of vortex rings and vortex pairs is investigated. The results of a vortex ring experiment, in which rings were injected into linear and discontinuous density stratifications, are compared with calculations of ring behavior made using an axisymmetric, unsteady solution of the mean variable and the modeled Reynolds stress equations. Second-order closure of the equations is based upon the invariant modeling technique of Donaldson. Comparisons are made for ring trajectories, radius, and size of the recirculation cell carried along with the ring. Calculations of turbulent vortex pairs descending into a stably stratified atmosphere are presented. The vortex separation for the two-dimensional calculation is found to be very nearly constant with vortex pair descent, while both the experimental and numerical results for vortex rings give a sharply decreasing radius during descent.

Hedenstrom, A.

"VORTEX WAKES OF BIRD FLIGHT: OLD THEORY, NEW DATA AND FUTURE PROSPECTS"

WIT Transactions on State of the Art in Science and Engineering, Vol. 4, 2006, pp. 706-734.

Flying birds leave a vortex wake. Fluid dynamic theory in the form of Helmholtz' theorems dictate the allowable topologies, and Kelvin's circulation theorem requires that changes in wake circulation are directly proportional to force changes on the wing/airfoil that generated the wake. Much bird flight research has therefore been focused on the properties of trailing wake vortices behind birds, since an accurate quantitative description of these will reveal also the aerodynamics of bird wings. The first vortex theory of bird flight assumed the periodic shedding of discrete vortex loops, each one generated during a downstroke, while the upstroke was considered aerodynamically functionless. This view received some support from early visualization experiments of take-off flight or very low speeds, while experiments at a higher speed ($U = 7$ m/s) in one species showed undulating wing-tip vortices of similar circulation on both down and upstroke. The necessary force asymmetry between downstroke and upstroke was obtained by wing flexing during the upstroke. Then followed an almost 20-year drought, with no further quantitative experiments, until recently when digital particle imaging velocimetry (DPIV) was successfully deployed in a low-turbulence wind tunnel, and where the same small (30 g) bird could be studied across a large range of flight speeds (4-11 m/s). These new experiments revealed a much more complicated wake pattern than previous data suggested, mainly due to the improved experimental resolution. The bird generated structures most closely resembling vortex loops at slow speeds, which gradually transformed into something like a constant circulation wake at the highest speeds. However, the wakes were never as clean as the idealized cartoon models of the vortex theory of bird flight, and previous paradoxical results were shown to be attributable to the resulting difficulty in accounting for all wake components. New DPIV data on other species indicate that these findings are quite general.

Hedenstrom, A., Johansson, L. C., Wolf, M., von Busse, R., Winter, Y. and Spedding, G. R.

"BAT FLIGHT GENERATES COMPLEX AERODYNAMIC TRACKS"

Science, Vol. 316, May 2007, pp. 894-898

The flapping flight of animals generates an aerodynamic footprint as a time-varying vortex wake in which the rate of momentum change represents the aerodynamic force. We showed that the wakes of a small bat species differ from those of birds in some important respects. In our bats, each wing generated its own vortex loop. Also, at moderate and high flight speeds, the circulation on the outer (hand) wing and the arm wing differed in sign during the upstroke, resulting in negative lift on the hand wing and positive lift on the arm wing. Our interpretations of the unsteady aerodynamic performance and function of membranous-winged, flapping flight should change modeling strategies for the study of equivalent natural and engineered flying devices.

Hedman, S. G.

"COMPUTATION OF VORTEX MODELS FOR WINGS AT HIGH ANGLE OF ATTACK IN INCOMPRESSIBLE FLOW"

FFA-AU-653, February 1973, Aeronautical Research Inst. of Sweden, Stockholm, Sweden

The vortex lattice method is applied in the solution of the thin wing lifting problem. The strength of the horseshoe vortices and a set of trailing vortex definition points are computed. The flow is required to be tangential at several collocation points on the wing and on the trailing vortices. This is expressed in a system of equations. It is shown how the system can be solved in two ways. In the first the system is partitioned into two subsystems, one where the boundary conditions of the wing are used for the determination of the vortex strengths, and one where the boundary conditions of the free vortices determine the positions of the vortices. In the second method the whole system is solved simultaneously by means of Newton-Raphson's rule.

Heffernan, K. G.

"TRAILING VORTEX ATTENUATION DEVICES"

M.S. Thesis, June 1985, Naval Postgraduate School, Monterey, CA

Trailing vortices generated by large aircraft pose a serious hazard to other planes. Numerous studies have been carried out to destroy them either before and/or after their formation. The present investigation is a survey and critical assessment of all the known active/passive devices and wingtip modifications proposed to achieve vortex attenuation. It is concluded that some devices, such as the wing tip sails, have promise in affecting the vortex roll-up in the vicinity of the aircraft. However, more data and analysis on this and other devices are needed before they can be incorporated into existing aircraft or future designs.

Heil, R. M.

"CHARACTERIZING THE WAKE VORTEX SIGNATURE FOR AN ACTIVE LINE OF SIGHT REMOTE SENSOR"

MS Thesis, August 1994, Clemson University, Clemson, SC.

A recurring phenomenon, described as a wake vortex, develops as an aircraft approaches the runway to land. As the aircraft moves along the runway, each of the wing tips generates a spiraling and expanding cone of air. During the lifetime of this turbulent event, conditions exist over the runway which can be hazardous to following aircraft, particularly when a small aircraft is following a large aircraft. Left to themselves, these twin vortex patterns will converge toward each other near the center of the runway, harmlessly dissipating through interaction with each other or by contact with the ground. Unfortunately, the time necessary to disperse the vortex is often not predictable, and at busy airports can severely impact terminal area productivity. Rudimentary methods of avoidance are in place. Generally, time delays between landing aircraft are based on what is required to protect a small aircraft. Existing ambient wind conditions can complicate the situation. Reliable detection and tracking of a wake vortex hazard is a major technical problem which can significantly impact runway

productivity. Landing minimums could be determined based on the actual hazard rather than imposed based on a worst-case scenario. This work focuses on using a wind field description of a wake vortex to generate line-of-sight Doppler velocity truth data appropriate to an arbitrarily located active sensor such as a high-resolution radar or lidar. The goal is to isolate a range Doppler signature of the vortex phenomenon that can be used to improve detection. Results are presented on use of a simplified model of a wake vortex pattern. However, the method of analysis can easily be applied to any vortex model used to generate a wind field snapshot. Results involving several scan strategies are shown for a point sensor with a range resolution of 1 to 4 meters. Vortex signatures presented appear to offer potential for detection and tracking.

Heil, R. M.

"CHARACTERIZING THE WAKE VORTEX SIGNATURE FOR AN ACTIVE LINE OF SIGHT REMOTE SENSOR"

NASA CR-197697, August 1994, Clemson Univ., Clemson, SC

A recurring phenomenon, described as a wake vortex, develops as an aircraft approaches the runway to land. As the aircraft moves along the runway, each of the wing tips generates a spiraling and expanding cone of air. During the lifetime of this turbulent event, conditions exist over the runway which can be hazardous to following aircraft, particularly when a small aircraft is following a large aircraft. Left to themselves, these twin vortex patterns will converge toward each other near the center of the runway, harmlessly dissipating through interaction with each other or by contact with the ground. Unfortunately, the time necessary to disperse the vortex is often not predictable, and at busy airports can severely impact terminal area productivity. Rudimentary methods of avoidance are in place. Generally, time delays between landing aircraft are based on what is required to protect a small aircraft. Existing ambient wind conditions can complicate the situation. Reliable detection and tracking of a wake vortex hazard is a major technical problem which can significantly impact runway productivity. Landing minimums could be determined based on the actual hazard rather than imposed because of a worst-case scenario. This work focuses on using a wind field description of a wake vortex to generate line-of-sight Doppler velocity truth data appropriate to an arbitrarily located active sensor such as a high-resolution radar or lidar. The goal is to isolate a range Doppler signature of the vortex phenomenon that can be used to improve detection. Results are presented on use of a simplified model of a wake vortex pattern. However, the method of analysis can easily be applied to any vortex model used to generate a wind field snapshot. Results involving several scan strategies are shown for a point sensor with a range resolution of 1 to 4 meters. Vortex signatures presented appear to offer potential for detection and tracking.

Hein, S. and Theofilis, V.

"ON INSTABILITY CHARACTERISTICS OF ISOLATED VORTICES AND MODELS OF TRAILING-VORTEX SYSTEMS"

Computers & Fluids, Vol. 33, 2004, pp. 741-753

This paper demonstrates the applicability of a two-dimensional eigenvalue problem approach to the study of linear instability of analytically constructed and numerically calculated models of trailing-vortex systems. Chebyshev collocation is used in the 2D eigenvalue problem solution to discretize two spatial directions on which non-axisymmetric vorticity distributions are defined, while the third, axial spatial direction is taken to be homogeneous and is resolved by a Fourier expansion. The leading eigenvalues of the matrix discretizing the equations which govern small-amplitude perturbations superimposed upon such a vorticity distribution are obtained by Arnoldi iteration. The present approach has been validated by comparison of its results on the problem of instability of an isolated Batchelor vortex. Here benchmark computations exist, employing classic instability analysis, in which the azimuthal direction is also treated as homogeneous. Subsequently, the proposed methodology has been shown to be able to recover the classic long- (Crow) and short-wavelength instabilities of a counter-rotating vortex-pair basic flow obtained by direct numerical simulation. Finally, the effect on the eigen-spectrum of the isolated Batchelor vortex is documented, when the basic flow consists of a linear superposition of such vortices. The modifications of the eigen-spectrum of a single vortex point to the potential pitfalls of drawing conclusions on the instability characteristics of a trailing-vortex system by monitoring the constituent vortices in isolation.

Heineck, J. T., Wadcock, A. J., Yamauchi, G. K., Lourenco, L. and Abrego, A. L.

"APPLICATION OF THREE-COMPONENT PIV TO A HOVERING ROTOR WAKE"

American Helicopter Society, 56th Annual Forum, May 2000, Virginia Beach, VA.

Three-component velocity measurements in the wake of a two-bladed rotor in hover were made using the Particle Image Velocimetry 'PIV' technique. The velocity fields were oriented in a plane normal to the rotor disk and were acquired for wake ages ranging from 0 to 270 degrees for one rotor thrust condition. The experimental setup and processing of the instantaneous images are discussed. Data averaging schemes are demonstrated to mitigate the smearing effects of vortex wander. The effect of vortex wander on the measured vortex core size is presented.

Heinrich, R.

"NUMERICAL SIMULATION OF WAKE-VORTEX ENCOUNTERS USING THE CHIMERA-TECHNIQUE"

In New Results in Numerical and Experimental Fluid Mechanics III, Notes on Numerical Fluid Mechanics, Vol. 77, Eds. Wagner, et al., Springer-Verlag, Berlin Heidelberg, 2002, pp. 74-81.

Within the EU-project WAVENC the block structured DLR-FLOWer code has been applied to the inviscid simulation of a wake vortex encounter of a generic aircraft. The incoming vortices of the preceding aircraft are prescribed at the inflow boundary of the computational domain. This allows to capture a mutual interaction between aircraft and incoming vortices. To transport the vortices without too big numerical losses from the inflow boundary to the aircraft, very fine Cartesian grids, so 'called vortex transport meshes', have been embedded into the grid structure. This is enabled by the Chimera technique implemented in the code. One main advantage of this strategy is, that no remeshing is

needed to perform a parametric study of the aircrafts position relative to the incoming vortices. Global forces and moments as well as pressure distributions obtained for different positions of the aircraft in the vortex disturbed flowfield show a good agreement to experimental data.

Heinrichs, R. M.

"WAKE VORTEX MEASUREMENTS WITH A CW 10.6-MICRON COHERENT LASER RADAR"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 235-246

CW coherent laser radar provides detailed vortex measurements at ranges less than or equal to 400 m. Lincoln Laboratory has collected simultaneous wake vortex and meteorological data at Memphis for validation of vortex behavior models. Vortex range estimated from the angular integral of velocity spectra versus velocity compare well with wind-line data. Vortex circulation is estimated from spectral maximum velocities. Circulations (especially of smaller aircraft) can be biased due to flow from neighboring vortex. Results agree well with theory when the bias is considered.

Heinrichs, R. M.

"OVERVIEW OF WAKE VORTEX DATA COLLECTION AND ANALYSIS AT MEMPHIS, JFK, AND DFW AIRPORTS"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Quebec, Canada, pp. 109-11.

Lincoln Laboratory has constructed and fielded a CW-coherent laser radar at the Memphis International Airport during November-December, and August, 1995, and more recently at Dallas/Ft. Worth in September, 1997. Wake vortex data were collected during these periods from a variety of aircraft, accompanied by simultaneous measurements of local meteorological conditions. These data have been used to correlate vortex behavior with local atmospheric parameters, such as winds, turbulence, and atmospheric stability. This presentation discusses the lidar configuration and data collection process. The basic configuration of the lidar and its performance capabilities are presented. The active vortex tracking capability of the lidar is also detailed along with algorithms developed for estimating vortex position and strength from lidar spectral data. Examples from the Memphis data set will be presented which demonstrate vortex behavior under various circumstances, such as out-of-ground effect and in-ground effect conditions.

Heinrichs, R. M. and Dasey, T. J.

"ANALYSIS OF CIRCULATION DATA FROM A WAKE VORTEX LIDAR"

AIAA Paper No. 1997-0059, Reno, NV, January 1997

The following paper presents the rationale and procedures used to estimate wake vortex circulation from data collected by a continuous-wave, 10.6-micron, coherent laser radar as well as selected results. These data have been collected during fielding at Memphis, TN in December 1994 and August 1995. Since the lidar measures line-of-sight (LOS) velocities, there is the potential for a bias of the circulation estimate of a vortex due to the velocity field of the neighboring, counter-rotating, vortex. An analytical expression is developed for the size of this effect for the case of the lidar looking straight up at a pair of vortices and a numerical model is developed for the case of the lidar observing a pair of equal altitude vortices at an arbitrary angle. The impact on LOS velocity determination from the spectral spreading of the lidar is also considered and an algorithm is developed which attempts to compensate for this effect. Comparisons of the averaged estimated vortex circulation for various individual aircraft are made with the initial theoretical circulation. Initial vortex circulations estimated from larger sets of aircraft measurements are also compared with theoretical expectations. As an independent confirmation of the circulation estimation procedure, 'virtual' lidar scans are numerically performed across vortex velocity fields generated from NASA computational models and the circulation estimates are compared with the actual circulations of the velocity field data. Finally, as an example of how the vortex circulation results can be analyzed, normalized circulation data is compared with the predictions from a model which accounts for atmospheric density profiles.

Heinrichs, R. M., Dasey, T. J., Matthews, M. P., Campbell, S. D., Freehart, R. E., Perras, G. H. and Salamitou, P.

"MEASUREMENTS OF AIRCRAFT WAKE VORTICES AT MEMPHIS INTERNATIONAL AIRPORT WITH A CW CO₂ COHERENT LASER RADAR"

SPIE Paper No. SPIE-2737-20, Orlando, FL, April 1996

A CW-coherent laser radar using a 20-Watt CO₂ laser has been constructed and deployed for the measurement of wake-vortex turbulence. This effort is part of the NASA Terminal Area Productivity Program and has the goal of providing information to further the understanding of the motion and decay of wake vortices as influenced by the local atmospheric conditions. To meet this goal, vortex measurements are made with the lidar along with simultaneous measurements from a suite of meteorological sensors which include a 150' instrumented tower, a profiler/RASS, sodar and balloon soundings. The information collected also includes airline flight data and beacon data. The operation of the lidar during two field deployments at Memphis International Airport are described as well as examples of vortex motion and decay measurements in various atmospheric conditions.

Heinrichs, R. M., Evans, J. E. and Primmerman, C. A.

"LASER SYSTEMS FOR CHARACTERIZATION AND MONITORING OF WAKE VORTICES"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 40-1 - 40-12

Adequate characterization of wake vortices by high-resolution (e.g., 30 cm downrange resolution), noninvasive, measurements in conjunction with measurements of local atmospheric conditions has been a long-standing requirement for operationally oriented studies. We describe a system to provide these high-resolution measurements based on a mode-locked, cavity-dumped, CO₂ laser. This system offers the capability of 1' x 1' spatial resolution along with 0.5 m/sec velocity resolution of a vortex. Such a system would also be able to extend the coherent integration time to measure velocities down to 5 - 10 cm/sec, thus enabling a measurement of the velocity turbulence in the ambient air towards which a vortex is heading. This measurement capability would provide input regarding the vortex structure and surrounding velocity turbulence for detailed modelling of vortex dynamics. Wake vortex monitoring as part of an advisory system can be accomplished with a coarser resolution than for characterization. For this application, long-term reliability and overall system cost are key issues. We suggest a system based on a diode-pumped cw solid-state laser at 2.1 microns because of its advantages of smaller optical aperture size, greater reliability, and lower cost over a CO₂ laser-based system. A set of these laser radars would be located beneath the glideslope to measure the average circulation and location of vortices at operationally relevant spatial scales. A point design based on existing solid-state laser technology is described.

Heinrichs, R. M., Freehart, R. E., Dasey, T. J., and Mandra, R. S.

"DEVELOPMENT AND PERFORMANCE OF A CW COHERENT LASER RADAR FOR DETECTING WAKE VORTICES"

Conference on Coherent Laser Radar, OSA, Keystone, CO, July 1995

A CW-coherent laser radar using a 20-Watt CO₂ laser has been constructed and deployed for the measurement of wake-vortex turbulence. This is part of a larger effort to understand the motion and decay of wake vortices as a function of local atmospheric conditions. The construction and operation of the lidar and the initial fielding at Memphis International Airport are described.

Heinrichs, R. M., Libby, J. C. and Dasey, T. J.

"WAKE VORTEX MEASUREMENTS WITH A CW COHERENT LASER RADAR OF THE XV-15 TILTROTOR AIRCRAFT"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Lincoln Laboratory, in coordination with Bell Helicopter Textron, has conducted measurements of the wake vortex characteristics of the XV-15 tiltrotor aircraft. Vortices generated in different forward flight configurations were detected and tracked by our mobile continuous-wave coherent CO₂ laser radar. This is the first time the wake of a tiltrotor aircraft has been measured using laser radar. The CW coherent laser radar was developed as part of the NASA AVOSS program. It has been employed over several measurement campaigns to collect wake-vortex data from fixed-wing landing aircraft while simultaneous measurements were performed to characterize the atmospheric state. The laser radar is

described along with examples of wake-vortex measurements of landing fixed-wing aircraft under the AVOSS program. Measurements made in August 2000 at the Bell Helicopter Test Flight Facility in Arlington, Texas are presented, along with an analysis of the vortex data.

Heintsch, T. and Kindel, W.

"REALTIME-SIMULATION OF AIRCRAFT BEHAVIOUR IN WAKE VORTICES WITH RESPECT TO FLIGHT SAFETY"

Proceedings 19th ICAS Congress, Anaheim, CA, September 18-19, 1994, AIAA, Vol. 1, pp. 529-540

Interactions between an aircraft and the vortex flow shed by another aircraft are presently explored by means of a real-time-capable vortex model; the aircraft simulation employed in this effort uses an aerodynamic lifting surface/lifting-line algorithm to determine vortex-induced forces and moments exerted on the aircraft that encounters the vortex. Attention is given to the vortex angle, the wingspan of the encountering aircraft relative to the vortex-core extension, and the weight and size of both the encountering and the generating aircraft.

Heister, S. D., McDonough, J. M., Karagozian, A. R. and Jenkins, D. W.

"THE COMPRESSIBLE VORTEX PAIR"

J. Fluid Mechanics, Vol. 220, 1990, pp. 339-354.

A numerical solution for the flow field associated with a compressible pair of counter-rotating vortices is developed. The compressible, two-dimensional potential equation is solved utilizing the numerical method of Osher et al for flow regions in which a non-zero density exists. Close to the vortex centers, vacuum 'cores' develop owing to the existence of a maximum achievable flow speed in a compressible flow field. A special treatment is required to represent these vacuum cores. Typical streamline patterns and core boundaries are obtained for upstream Mach numbers as high as 0.3, and the formation of weak shocks is observed.

Helmis, C. G., Kalogiros, J. A., Asimakopoulos, D. N. and Soilemes, A. T.

"ESTIMATION OF POTENTIAL-TEMPERATURE GRADIENT IN TURBULENT STABLE LAYERS USING ACOUSTIC SOUNDER MEASUREMENTS"

Quarterly Journal of the Royal Meteorological Society, Vol. 126, 2000, pp. 31-61.

The intensity of acoustic backscatter from a monostatic acoustic sounder is used to compute the profile of the temperature structure parameter $C_{\text{sub}} T^2$. The average value of $C_{\text{sub}} T^2$ in low-height turbulent stable layers (temperature inversions) is used to infer the local potential-temperature gradient. The estimates of temperature jump in the first height inversion at the top of the unstable atmospheric boundary layer (ABL) are compared with the direct measurements of the temperature profile by a tethered balloon, and the indirect estimation from the wave period of the

waves present on the inversion. The agreement of the estimations with the direct measurements is satisfactory (at least a 0.4 deg C accuracy). Also, the $-4/3$ similarity law of the $C_{sub T}$ squared profile in the unstable ABL is used to obtain estimates of the surface heat flux, $Q_{sub 0}$. The comparison of these estimates of $Q_{sub 0}$ with eddy correlation measurements shows the high accuracy of this method. This direct connection of the $C_{sub T}$ squared profile with $Q_{sub 0}$ can also be used to calibrate the backscatter intensity.

Helmke, H., Hann, R., Uebbing-Rumke, M., Muller, D. and Wittkowski, D.

"TIME-BASED ARRIVAL MANAGEMENT FOR DUAL THRESHOLD OPERATION AND CONTINUOUS DESCENT APPROACHES"

Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009), June 2009, Napa, CA.

The paper deals with the successive application of time-based arrival management and automatic arrival-departure-coordination. DLR's arrival manager 4D-CARMA supports approach controllers with sequence and advisory information during two time-based human-in-the-loop experiments: First 4D-CARMA was used for dual threshold operation on a parallel runway system operated in mixed mode for arrivals and departures. The dual threshold operation was performed within the context of the OPTIMAL project of the European commission. Particular consideration is given in this paper to the validation exercises performed with three different European controller teams. An increase of the inbound flow of 3 to 4 arrivals per hour without negative impact on the outbound flow and on controller workload is possible if automatic arrival-departure-coordination together with advisory information is provided to the controllers. In an additional human-in-the-loop experiment 4D-CARMA supports the controllers to integrate unequipped aircraft into a stream of 4D equipped ones performing a user-preferred CDA approach.

Hemati, M. S., Eldredge, J. D. and Speyer, J. L.

"WAKE SENSING FOR AIRCRAFT FORMATION FLIGHT"

AIAA Paper No. 2012-4768, August 2012, Minneapolis, Minnesota.

It is well established that flying aircraft in formation can lead to improved aerodynamic efficiency. However, successfully doing so is predicated on having knowledge of the lead aircraft's wake position. Here, we develop a wake sensing strategy to estimate the wake position and strength in a two-aircraft formation. The wake estimator synthesizes wing-distributed pressure measurements, taken on the trailing aircraft, by making use of an augmented lifting line model in conjunction with both Kalman-type and particle filters. The various estimation algorithms are tested in a vortex-lattice simulation environment, thus enabling the effects of modeling error to be analyzed. It is found that biases in the position estimates no longer arise if a particle filter is used in place of the Kalman-type filters. Filter divergence is observed when the relative aircraft separations are held fixed. This divergent behavior can

be alleviated with the introduction of relative aircraft motions, for example in the form of a cross-track dither signal.

Hemati, M. S., Eldredge, J. D. and Speyer, J. L.

"WAKE SENSING FOR AIRCRAFT FORMATION FLIGHT"

Journal of Guidance, Control and Dynamics, Vol. 37, No. 2, March-April 2014, pp. 513-524.

It is well established that flying aircraft in formation can lead to improved aerodynamic efficiency. However, successfully doing so is predicated on having knowledge of the lead aircraft's wake position. Here, a wake-sensing strategy for estimating the wake position and strength in a two-aircraft formation is explored in a simplified proof-of-concept setting. The wake estimator synthesizes wing-distributed pressure measurements, taken on the trailing aircraft, by making use of an augmented lifting-line model in conjunction with both Kalman-type and particle filters. Simple aerodynamic models are introduced in constructing the filter to enable fundamental wake-sensing challenges to be identified and reconciled. The various estimation algorithms are tested in a vortex lattice simulation environment, thus allowing the effects of modeling error to be analyzed. It is found that biases in the position estimates no longer arise if a particle filter is used in place of the Kalman-type filters. Filter divergence is observed when the relative aircraft separations are held fixed. This divergent behavior can be alleviated with the introduction of relative aircraft motions, for example in the form of a cross-track dither signal.

Hemm, R.

"BUSINESS CASE ANALYSIS FOR NASA WAKE VORTEX TECHNOLOGY"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

This briefing summarizes a business case analysis for the Wake Vortex Advisory System (WVAS) technology being developed by NASA and related technologies being developed by the Federal Aviation Administration (FAA). The technologies modeled in the current task include simultaneous offset instrument approaches (SOIA), dependent (staggered) arrivals on closely-spaced parallel runways (CSPRs), and reduced arrival and departure miles-in-trail (MIT) separations. The briefing will summarize the analysis with a focus on the role of meteorological data. The use of SOIA avoids air traffic control wake vortex constraints by expanding the visual operating conditions under which aircrews, not controllers, are responsible for wake vortex separation. SOIA procedures allow visual operations under reduced, but not IFR, ceiling and visibility limits. SOIA benefits were estimated by including the appropriate SOIA ceiling and visibility in airport delay model meteorological condition selection rules. CSPR procedures allow dependent (staggered) approaches to parallel runways with centerline separations less than 2500 feet. Near-term FAA weather-independent CSPR procedures are limited to Small- and Large-class aircraft. Mid- and Far-term CSPR procedures are weather dependent and apply to all aircraft classes. Reduced MIT is also weather dependent. CSPR and reduced MIT benefits are

estimated by using airport capacity models to generate various CSPR and MIT configurations and selecting those configurations in airport delay models when specified conditions (e.g., wind limits) are met. The analysis includes three individual airport studies - San Francisco, St. Louis, and Dallas/Fort Worth. Two of the airports, San Francisco and St. Louis, suffer from significant delays and provide good models for examining the benefits of improved operating procedures for both CSPRs and MIT. While Dallas/Fort Worth benefits derive solely from reducing MIT, it was the demonstration site for the Aircraft Vortex Spacing System AVOSS in 2000, and the considerable data collected could potentially be used to corroborate assumptions made in predicting benefits.

Hemm, R. and Shapiro, G.

"TERMINAL AREA PRODUCTIVITY AIRPORT WIND ANALYSIS AND CHICAGO O'HARE MODEL DESCRIPTION"

NASA CR-207662, April 1998, NASA Langley Research Center, Hampton, VA

This paper describes two results from a continuing effort to provide accurate cost-benefit analyses of the NASA Terminal Area Productivity (TAP) program technologies. Previous tasks have developed airport capacity and delay models and completed preliminary cost benefit estimates for TAP technologies at 10 U.S. airports. This task covers two improvements to the capacity and delay models. The first improvement is the completion of a detailed model set for the Chicago O'Hare (ORD) airport. Previous analyses used a more general model to estimate the benefits for ORD. This paper contains a description of the model details with results corresponding to current conditions. The second improvement is the development of specific wind speed and direction criteria for use in the delay models to predict when the Aircraft Vortex Spacing system (AVOSS) will allow use of reduced landing separations. This paper includes a description of the criteria and an estimate of AVOSS utility for 10 airports based on analysis of 35 years of weather data.

Hemm, R. V., Eckhause, J. M., Long, D., Stouffer, V. and Hees, J.

"BUSINESS CASE ANALYSIS FOR NASA WAKE VORTEX TECHNOLOGY"

LMI-NS254T1, March 2004, Logistics Management Institute, McLean, VA

Building on the wake vortex technology developed under the Aircraft Vortex Spacing System (AVOSS) program in the 1990's, NASA is developing an updated system - the Wake Vortex Advisory System (WVAS). The Federal Aviation Administration is also pursuing ways to improve capacity at congested airports through reduction of overly conservative wake vortex separations. NASA and FAA have coordinated their wake vortex efforts through development and use of a joint Research Management Plan (RMP). This business case analysis addresses the procedures and technologies being pursued under the RMP. The analysis quantitatively estimates the impact on delay at three individual airports - San Francisco, St. Louis, and Dallas/Ft. Worth - and the delay impact of deploying WVAS at 18 airports in a network of 64 airports. The report includes estimates of WVAS life-cycle costs for all 18 airports, and benefit-to-cost and net present value results for the three individual airports.

Hemm, R., Shapiro, G., Lee, D. A., Gribko, J. and Glaser, B.

"BENEFIT ESTIMATES OF TERMINAL AREA PRODUCTIVITY PROGRAM TECHNOLOGIES"

NASA CR-1999-208989, January 1999, Logistics Mgmt. Inst., McLean, VA

This report documents benefit analyses for the NASA Terminal Area Technology (TAP) technology programs. Benefits are based on reductions in arrival delays at ten major airports over the 10 years from 2006 through 2015. Detailed analytic airport capacity and delay models were constructed to produce the estimates. The goal of TAP is to enable good weather operations tempos in all weather conditions. The TAP program includes technologies to measure and predict runway occupancy times, reduce runway occupancy times in bad weather, accurately predict wake vortex hazards, and couple controller automation with aircraft flight management systems. The report presents and discusses the estimate results and describes the models. Three appendixes document the model algorithms and discuss the input parameters selected for the TAP technologies. The fourth appendix is the user's guide for the models. The results indicate that the combined benefits for all TAP technologies at all 10 airports range from \$550 to \$650 million per year (in constant 1997 dollars). Additional benefits will accrue from reductions in departure delays. Departure delay benefits are calculated by the current models.

Hensch, M. J. and Luckring, J. M.

"CONNECTION BETWEEN LEADING-EDGE SWEEP, VORTEX LIFT, AND VORTEX STRENGTH FOR DELTA WINGS"

Journal of Aircraft, Vol. 27, No. 5, May 1990, pp. 473-475.

In this Note the difference between nonlinear lift and vortex lift has been distinguished. The nonlinear lift is the difference between the actual lift at a given angle of attack and that given by the product of the slope of the lift coefficient at zero angle of attack times the angle of attack. The vortex lift is the increment of lift above the zero leading-edge suction attached-flow lift and is due to the presence of the leading-edge vortex. Using similarity and several experimental and computational results, it has been possible to show that the effect of increasing leading-edge sweep for slender delta wings is to decrease vortex lift and leading-edge vortex strength. These results are useful for the development of future design strategies for high angle-of-attack wing performance when it is desired to tailor the growth of the leading-edge vortices using sweep, camber, and leading-edge shape.

Henderson, S. W.

"REVIEW OF FUNDAMENTAL CHARACTERISTICS OF COHERENT AND DIRECT DETECTION DOPPLER RECEIVERS AND IMPLICATIONS TO WIND LIDAR SYSTEM DESIGN"

17th CLRC, Review of Fundamental Characteristics of Coherent and Direct Detection Doppler Receivers, June 2013, Barcelona, Spain.

Coherent and direct detection lidar systems for wind measurement applications have many similarities but differ fundamentally in photon detection and frequency estimation sensitivity. In this paper we review the key characteristics of each receiver type and implications of these fundamental characteristics on the design of Doppler measurement lidar systems. Although signals from aerosol and molecular scattering are included in the discussion, the emphasis in this paper is on systems utilizing narrowband aerosol backscatter for the wind measurement. Simplified system designs and approximate equations are used to better illustrate the fundamental characteristics of each receiver type without being bogged down by fine design details of any given system. Of course more detail must be added, beyond what is presented here, in order to describe the performance of any specific real lidar system to a high level of fidelity.

Henderson, S. W., Suni, P. J. M., Hale, C. P., Hannon, S. M., Magee, J. R., Bruns, D. I. and Yuen, E. H.

"COHERENT LASER RADAR AT 2 MICRONS USING SOLID-STATE LASERS"

IEEE Transactions on Geoscience and Remote Sensing, Vol. 31, No. 1, January 1993, pp. 1-15.

Coherent laser radar systems using 2-micron Tm- and Tm, Ho-doped solid-state lasers are useful for the remote range-resolved measurement of atmospheric winds, aerosol backscatter, and DIAL measurements of atmospheric water vapor and CO₂ concentrations. Recent measurements made with a 2-micron coherent laser radar system, advances in the laser technology, and atmospheric propagation effects on 2-micron coherent lidar performance are described.

Hennemann, I.

"DEFORMATION UND ZERFALL VON FLUGZEUGWIRBELSCHLEPPEN IN TURBULENTER UND STABIL GESCHICHTETER ATMOSPHERE"

Dr.-Ing. Thesis, February 2010, University of Munich, Munich, Germany.

Aircraft wake vortices have been observed to often live much longer than expected. Following aircraft encountering the wake vortices experience a rolling moment which depends on the deformation of the vortices. With the help of Large-Eddy Simulations, this work investigates the dynamics of wake vortices in a turbulent and stratified atmosphere. Particularly, a method was developed which precisely determines the vortex core line. For the first time, the curvature of that line was analyzed in sections. The results show that the frequency of vortex ring formation is astonishingly high. The descent speed of vortex rings is reduced and the circulation changes from flight direction to span wise direction. Before linking, mean curvature radii of the vortices reduce to the size of one initial vortex spacing. After linking, they may grow again. The expected rolling moment of following aircraft is estimated. In particular, the comparison with field measurement data obtained within the EU project AWIATOR confirms the presented results. [In German.]

Hennemann, I. and Holzaepfel, F.

"LARGE-EDDY SIMULATION OF AIRCRAFT WAKE VORTEX DEFORMATION AND TOPOLOGY"

Proceedings of IMechE, Vol. 225, Part G, 2011, pp. 1336-1350.

On the one hand, it is known from visual observations, Lidar measurements, and numerical simulations that aircraft wake vortices may live longer than anticipated by today's standard regulations of air traffic control. On the other hand, the initially counter-rotating, parallel vortex pair deforms quickly, which reduces the impact time of adverse forces and moments on encountering aircraft. Therefore, large-eddy simulations of wake vortex evolution in different meteorological conditions are conducted to analyze the physics of vortex deformation. A new post-processing algorithm has been developed that at first determines the three-dimensional path of the vortex core line and then computes piecewise curvature radii as a measure of vortex deformation. It is found that larger turbulence levels and neutral to weakly stable temperature stratification particularly support vortex ring formation. The vortex ring regime is characterized by a reduced descent rate and by a surprising variability of its core radius. It is shown that the varying core size directly affects the evolution of radius-averaged circulation. Comparisons with field experiments indicate good agreement with the considerable life time of the vortex rings and topology.

Hennemann, I. and Holzapfel, F.

"AIRCRAFT WAKE VORTEX DEFORMATION IN TURBULENT ATMOSPHERE"

5th International Symposium on Turbulence and Shear Flow Phenomena, Munich, August 2007

Large-scale distortion of aircraft wake vortices appears to play a crucial role for aircraft safety during approach and landing. Vortex distortion is investigated based on large eddy simulations of wake vortex evolution in a turbulent atmosphere. A vortex identification method is developed that can be adapted to the vortex scales of interest. Based on the identified vortex center tracks, a statistics of vortex curvature radii is established. These statistics constitute the basis for understanding, modeling, and exploiting mitigation effects of vortex distortion on wake vortex encounters.

Herder, A. J.

"AIRCRAFT WAKE TURBULENCE AWARENESS"

US Patent Application 2016/0328981 A1, November 2016.

An avionics wake-turbulence awareness system and method for use in an aircraft includes an ADS-B receiver that is adapted to be positioned in an equipped aircraft and receives ADS-B transmissions from other aircraft. A control system is responsive to the ADS-B receiver and determines an identity for each of the other aircraft and determines a movement of each of the other aircraft relative to the equipped aircraft. The control system determines a flight path history of each of the other aircraft from their respective identities and movements relative to the equipped aircraft. An output device is responsive to the control system to provide guidance to a pilot of the equipped aircraft to avoid an encounter with a wake turbulence caution area that is defined by a flight path history of another aircraft. The control

system evaluates the relative risk of the equipped aircraft encountering the respective wake turbulence caution areas of each of the other aircraft, and after selecting an aircraft of the other aircraft with a highest priority, provides guidance to the pilot of the equipped aircraft to avoid an encounter with a wake turbulence caution area of the selected aircraft.

Hernandez-Rivera, R., Hernandez-Guerrero, A., Rubio-Arana, C. and Arroyo, R. L.

"NUMERICAL STUDY IN WING TIP VORTEX FOR A MODIFIED COMMERCIAL BOEING AIRCRAFT"

Proceedings 2008 ASME International Mechanical Engineering Congress, IMECE2008-68149, Nov. 2008, Boston, MA.

Recent studies have shown that the use of winglets in aircrafts wing tips have been able to reduce fuel consumption by reducing the lift-induced drag caused by wing tip vortex. This paper presents a 3-D numerical study to analyze the drag and lift forces, and the behavior of the vortices generated in the wing tips from a modified commercial Boeing aircraft 767-300/ER. This type of aircraft does not contain winglets to control the wing tip vortex, therefore, the aerodynamic effects were analyzed adding two models of winglets to the wing tip. The first one is the vortex diffuser winglet and the second one is the tip fence winglet. The analyses were made for steady state and compressible flow, for a constant Mach number. The results show that the vortex diffuser winglet gives the best results, reducing the core velocity of the wing tip vortex up to 19%, the total drag force of the aircraft up to 3.6% and it leads to a lift increase of up to 2.4% with respect to the original aircraft without winglets.

Heron, I. And Myose, R. Y.

"VORTEX BURST BEHAVIOR UNDER DYNAMIC FREESTREAM"

AIAA Paper No. 2005-63, Reno, NV, January 2005

A series of experiments on a 70-degree delta wing was conducted at Wichita State University to study the effect on the vortex burst position when simultaneous dynamic pitch and unsteady freestream velocity were used. The aim was to better understand the relationship between the freestream velocity and the time constants involved in the movement of the vortex burst point. Experiments indicated that a change in the freestream velocity resulted in a momentary pause in the forward progression of the vortex burst of the leading-edge vortex.

Heron, I. and Myose, R. Y.

"IMPINGEMENT OF A VON KARMAN VORTEX STREET ON A DELTA WING"

Journal of Aircraft, Vol. 42, No. 4, July-August 2005, pp. 1084-1087.

A series of experiments, where a von Karman vortex street wake was made to impinge upon a 70-deg delta wing, was conducted at Wichita State University using a towing mount. There was a temporal correlation to the burst location of the delta wing's leading edge (LE) vortices, which indicated

modulation of the burst location. The LE vortex burst location moved forward towards the apex with the passing of the filaments. This jump was most noticeable at lower angles of attack. It was also found that the average vortex-burst location remained approximately the same whether the freestream flow was clean or in the wake. Qualitatively, as the von Karman vortex filaments were entrained by the shear layer, they appeared to wrap themselves around the core. Additionally, there was a small-amplitude wave distortion of the LE core. Dye concentrations at regular intervals were also observed in the LE vortex core.

Herrada, M. A. and Barrero, A.

"NONPARALLEL LINEAR STABILITY ANALYSIS OF UNCONFINED VORTICES"

Physics of Fluids, Vol. 16, No. 10, Oct. 2004, pp. 3755-3764.

Parabolized stability equations have been used to study the stability of a family of swirling jets at high Reynolds numbers whose velocity and pressure fields decay far from the axis as r to $m-2$ power and r to $2(m-2)$ power, respectively; r is the radial distance and m is a real number in the interval $0 < m < 2$. Results show that the nonparallel effects of the basic flow play an important role in the development of both axisymmetric and non-axisymmetric unstable perturbations upstream of the vortex breakdown station. A complementary local nonparallel analysis shows the convective nature of these instabilities. Therefore, a criterion based on the transition from convective to absolute instabilities cannot be applied to predict the vortex breakdown of this kind of swirling jets. On the contrary, the failure of the quasi-cylindrical approximation used to compute the downstream evolution of the basic flow gives a clear breakdown criterion based on the catastrophic transition between slender and non-slender flows.

Herrada, M. A. and Shtern, V.

"CONTROL OF VORTEX BREAKDOWN BY TEMPERATURE GRADIENTS"

Physics of Fluids, Vol. 15, No. 11, November 2003, pp. 3468-3477

An axial gradient of temperature can either suppress or enhance vortex breakdown (VB). The underlying mechanism of such VB control is centrifugal or/and gravitational convection. An additional thermal-convection flow directed oppositely to the base flow suppresses VB while a co-flow enhances VB. Our numerical simulations of a compressible flow in a sealed cylinder induced by a rotating bottom disk clearly reveal these effects. We vary the temperature gradient, Mach (Ma), Froude (Fr), and Reynolds (Re) numbers, and the aspect ratio (h). As E increases ($E > 0$ corresponding to a temperature gradient parallel to the downward near-axis flow), the VB 'bubble' which occurs at $E = 0$, diminishes and then totally disappears. The opposite temperature gradient ($E < 0$) enlarges the VB bubble and makes the flow unsteady. These effects of centrifugal convection become more prominent with increasing Ma and Re . Density variations induced by the temperature gradients are more important for VB control than those induced by the increase in Ma . A new efficient time-evolution code for axisymmetric flows of an ideal gas has facilitated these simulations.

Herrada, M. A., Perez-Saborid, M. and Barrero, A.

"VORTEX BREAKDOWN IN COMPRESSIBLE FLOWS IN PIPES"

Physics of Fluids, Vol. 15, No. 8, August 2003, pp. 2208-2218

The effects of compressibility on vortex flows in pipes have been analyzed using both the axisymmetric Navier-Stokes (NS) equations and the quasi-cylindrical (QC) approximation. Numerical simulations of the full axisymmetric NS equations show that, for sufficiently large values of the Reynolds number, compressible flows present a multiplicity of steady-state solutions in a range of values of the swirl strength. The sensitivity of the vortex flow structure to the parameters of the problem: Mach number, Reynolds number, velocity profiles at the pipe entrance and pipe geometry has been also investigated. In particular, the critical swirl parameter necessary for the occurrence of vortex breakdown has been determined as a function of both the Mach number and the axial momentum of the flow at the pipe entrance. For large Reynolds number, the results of the QC approximation are found to be in good agreement with those of the full NS simulations. These results show that the upstream propagation of the sound waves seems to have a negligible influence on vortex breakdown and give support to the use of the QC approximation for the study of some aspects of the compressible swirling flows.

Herrema, F.

"TIME BASED SEPARATION COMPRESSION ON FINAL APPROACH AND TIME BASED SEPARATION FOR OPTIMIZED RUNWAY DELIVERY"

MS Thesis, December 2014, Delft University of Technology, Delft, The Netherlands.

For going over Distance Based Separation (DBS) and modelling a Time Based Separation (TBS) concept, a better characterization of the compression effect is required, which is the main goal of this report. Actual distance-based separations are to be replaced by time intervals, and/or speed compensation. The problem is that the aircraft pair (leader-follower) flying different point on final approach differs in its speeds, causing the separation between the two paired aircraft to increase or decrease. Decreasing separation below the minima increases the risk of wake turbulence encounters. In addition, the headwind conditions should be considered since these will reduce the groundspeed and as such the time to fly when no speed compensation is applied. This study will predominately focus on these headwind conditions. The characterization issues extracted in this study are needed to feed or support the TBS FFH tool for building an airspeed profile for the leader and follower aircraft on final approach. The tool can include the following characterization effects: Approach Speed (V_{app}), Deceleration and Stabilization Fix (DF & SF) and Glide Slope Speed. These performance parameters depend on the, aircraft type (wingspan/speed), wind profile, manufacturer (Airbus or Boeing), airline, part of the day and STAR. However, other challenging compression issues such as Time to Fly, current time separation, pilot/ATC practices and the Flight Management System (FMS) have also been analyzed in extensive detail and will act as recommendation for the future TBS studies. The data supporting the above conclusions is obtained from Charles De Gaulle (CDG) airport. To improve verification the results are compared with data from Vienna airport and show significant similarities, noting that DF and SF

standard deviations are higher compared to the TAS and time to fly due to local ILS and IAP procedures. A comparison of CDG approach speed profiles with the data used in RECAT-EU and Boeing data also shows significant similarities. In two case studies the new TBS FFH tool and the TBS OSED 1 tool are tested against real radar tracks. By comparing the performances of these two models, the best performances are extracted by looking at the least time separation error. In both studies the TBS FFH tool performed better. Finally, approach speeds, DF & SF and glide slope speeds resulting from this study have been used as input parameters in the SESAR Project 06.08.01 Validation Exercise for the TBS OSED Phase 2 model. Primarily results from this exercise indicate an improvement in runway throughput recovery applying the new TBS methodology when comparing low wind with high wind conditions.

Herrema, F. F., Zhao, W., Curran, R., Treve, V. and Graham, R.

"TIME BASED SEPARATION: COMPRESSION ON FINAL APPROACH AND TIME BASED SEPARATION FOR OPTIMIZED RUNWAY DELIVERY"

AIAA Paper 2015-2430, June 2015, Dallas, TX.

In this research, firstly individual characterization performances are examined, such as, the time to fly, the deceleration and stabilization fix, airspeeds, aircraft type and flight manual system. This will be done for a better understanding of the speed profile and the compression effect on final approach. Secondly, these performances will be verified with Vienna airport, RECAT-EU and Boeing data and incorporated into a DBS model. Thirdly, the model will be translated into a TBS FFH (Floris Friso Herrema) model by giving as input the most relevant extracted characterization issues. Finally, the report shows two case studies, in which TBS FFH and TBS OSED 1 models are tested in real radar tracks, using both Airbus and Boeing medium aircraft types. By comparing the performances of these two TBS models, the best performances will be extracted by looking at the least time separation error. The innovation of this study is that the aircraft performances, runway compression issues and air traffic control solutions for applying TBS are now, for the first time, captured mathematically in a model, to evaluate the system requirements and constraints to cater to compression. With this model the potential performance improvements and related compression issues by using a TBS methodology, can be predicted.

Herrema, F., Treve, V., Desart, B., Curran, R. and Visser, D.

"A NOVEL MACHINE LEARNING MODEL TO PREDICT ABNORMAL RUNWAY OCCUPANCY TIMES AND OBSERVE RELATED PRECURSORS"

12th USA/Europe Air Traffic Management Research and Development Seminar (ATM2017), June 2017, Seattle, WA.

Accidents on the runway triggered the development and implementation of mitigation strategies. Therefore, the airline industry is moving toward proactive risk management, which aims to identify and predict risk precursors and to mitigate risks before accidents occur. For certain predictions Machine

Learning techniques can be used. Although many studies have explored and applied novel Machine Learning techniques on different aircraft Radar and operational Taxi data, the identification and prediction of abnormal Runway Occupancy Times and the observation of related precursors are not well developed. In our previous papers, three feasible methods were introduced: Lasso, Multi-Layer Perception and Neural Networks to predict the Taxi-Out Time on the taxiway and the Time to Fly and True Airspeed profile on final approach. This paper presents a new Machine Learning method, where we merge these feasible Machine Learning techniques for predicting the abnormal Runway Occupancy Times of unique radar data patterns. Additionally, we use in this study the Regression Tree method to observe key related precursors extracted from the top 10 features. Compared with existing methods, the new method no longer requires predefined criteria or domain knowledge. Tests were conducted using runway and final approach aircraft radar data consisting of 78,321 Charles de Gaulle flights and were benchmarked against 500,000 Vienna flights.

Herring, G. C.

"NONINVASIVE MEASUREMENT OF VELOCITY, PRESSURE, AND TEMPERATURE IN UNSEEDED SUPERSONIC AIR VORTICES"

Journal of Aircraft, Vol. 46, No. 3, May-June 2009, pp. 1074-1076.

In summary, novel nonintrusive time-averaged point measurements of velocity, pressure, and temperature have been demonstrated with vertical height profiles through the low-density vortex core from a supersonic delta wing. The present work illustrates the potential of the SRGS laser diagnostic for noninvasive and quantitative off-body flow measurements for many applications such as vortex and other flow field studies, wind-tunnel optimization, and validation of computational fluid dynamics.

Hess, R. A.

"ASSESSING WAKE VORTEX HAZARDS USING PILOT/VEHICLE ANALYSES"

In: Advances in Human Aspects of Aviation, edited by W. Karwowski, CRC Press, 2012, Chapter 55, pp. 581-592.

The development of a methodology that will allow the assessment of hazards associated with wake-vortex encounters by fixed and rotary-wing aircraft is presented. The methodology utilizes pilot/vehicle analyses and is intended to serve as a prelude to high-fidelity pilot-in-the-loop flight simulation. The pilot model, itself, has been introduced in the literature for flight simulator fidelity investigations. The analysis procedure provides an economical and time-saving tool for preliminary assessment of wake vortex hazards. The approach is exercised using a model of a small business jet as an in-trail aircraft interacting with a relatively simple vortex model assume generated by a large transport aircraft. Hazard metrics are proposed and employed in the analysis. The possibility of wake vortex-induced upsets providing triggering events for pilot-induced oscillations is emphasized.

Hesse, H. and Palacios, R.

"DYNAMIC LOAD ALLEVIATION IN WAKE VORTEX ENCOUNTERS"

Journal of Guidance, Control, and Dynamics, Vol. 34, No. 4, April 2016, pp. 801-813.

This paper introduces an integrated approach for flexible-aircraft time-domain aeroelastic simulation and controller design suitable for wake encounter situations. The dynamic response of the vehicle, which may be subject to large wing deformations in trimmed flight, is described by a geometrically nonlinear finite-element model. The aerodynamics are modeled using the unsteady vortex lattice method and include the arbitrary time-domain downwash distributions of a wake encounter. A consistent linearization in the structural degrees of freedom enables the use of balancing methods to reduce the problem size while retaining the nonlinear terms in the rigid-body equations. Numerical studies on a high-altitude, long-endurance aircraft demonstrate the reduced-order modeling approach for load calculations in wake vortex encounters over a large parameter space. Closed-loop results finally explore the potential of combining feedforward/feedback H_∞ control and distributed control surfaces to obtain significant load reductions.

Hesse, H. and Palacios, R.

"DYNAMIC LOAD ALLEVIATION OF FLEXIBLE AIRCRAFT IN WAKE VORTEX ENCOUNTERS"

International Forum on Aeroelasticity and Structural Dynamics, June-July 2015, Saint Petersburg, Russia.

This paper introduces an integrated approach for flexible-aircraft time-domain aeroelastic simulation and controller design suitable for wake encounter situations. The dynamic response of the vehicle, which may be subject to large wing deformations in trimmed flight, is described by a geometrically-nonlinear composite-beam finite-element model. The aerodynamics is modeled using the unsteady vortex lattice method and includes the arbitrary time-domain downwash distributions of a wake encounter. A consistent linearization in the structural degrees of freedom enables the use of balancing methods to reduce the problem size while retaining the nonlinear terms in the rigid-body equations. Numerical studies on a very flexible aircraft demonstrate the reduced-order modeling approach for load calculations in wake vortex encounters over a large parameter space. Closed-loop results finally explore the potential of combining feedforward/feedback H_∞ control and conventional control surfaces for load alleviation.

Hewitt, R. E. and Duck, P. W.

"LONG'S VORTEX REVISITED"

Journal of Fluid Mechanics, Vol. 634, 2009, pp. 91-111.

We consider exact solutions to the Navier-Stokes equations that describe a vortex in a viscous, incompressible fluid. This type of solution was first introduced by Long and is parameterized by an inverse Reynolds number ϵ . Long's attention (and that of many subsequent investigators) was centered

upon the 'quasi-cylindrical' (QC) case corresponding to $e = 0$. We show that the limit e going to 0 is not straightforward, and that it reveals other solutions to this fundamental exact reduction of the Navier-Stokes system (which are not of QC form). Through careful numerical investigation, supported by asymptotic descriptions, we identify new solutions and describe the full parameter space that is spanned by e and the pressure at the vortex core. Some erroneous results that exist in the literature are corrected.

Heyes, A. L. and Smith, D. A. R.

"MODIFICATION OF A WING TIP VORTEX BY VORTEX GENERATORS"

Aerospace Science and Tech., Vol. 9, 2005, pp. 469-475

The vortex wake hazard associated with transport aircraft is well known. One strategy for its alleviation is to alter the near field wake topology to distribute circulation over an increased area and reduce the consequent rolling moment on a following aircraft encountering the wake. The paper describes the results of an experimental investigation of the use of supplementary vortex generators to modify the tip vortex shed from a half-span airfoil. The experiments were conducted in a small low speed wind tunnel at a chord Reynolds number of $2.2 \times 100,000$ and the flow was characterized by measurement of the instantaneous and mean cross-stream flow field using particle image velocimetry. The results show that when the vortex generator is configured to produce a vortex that is co-rotating with respect to the wing-tip vortex, the two merge within five chord-lengths of the trailing edge resulting in a vortex with increased size relative to that of the baseline wake. Various vortex generator geometries were tested. A semi-circular generator produced an increase in core radius by a factor of five but the best shape was deemed triangular since generators of this shape produced substantial vortex enlargement with relatively low lift penalty. Low slenderness ratio generators were also deemed preferable since for a high slenderness generator it was shown that merging failed due to a negative vorticity buffer constrained to the region between the tip and generator vortex by the proximity of the generator vortex to the wing surface. Increasing the generator angle of attack was shown to increase the effectiveness of circulation redistribution. At the highest angles of attack increases occurred despite a decrease in VG vortex strength due to stalling. Unsteadiness in the stalled VG flow appears to enhance vorticity diffusion and it is hypothesized that it may also initiate cooperative instabilities in multiple vortex systems.

Heyes, A. L. and Smith, D. A. R.

"SPATIAL PERTURBATION OF A WING-TIP VORTEX USING PULSED SPAN-WISE JETS"

Experiments in Fluids, Vol. 37, 2004, pp. 120-127

The separation distance required between transport aircraft to avoid wake vortices remains a limiting factor on airport capacity. The dissipation of the wake can be accelerated by perturbing co-operative instabilities between multiple pairs of vortices. This paper presents the results of a preliminary experimental investigation into the use of pulsed span-wise air jets in the wing tip to perturb a single

tip vortex in the very near field. Velocity measurements were made using PIV and hot-wire anemometry. The results demonstrate that the vortex position can be modulated at frequencies up to 50 Hz and, as such, the method shows promise for forcing instability in multiple vortex wakes.

Heyes, A. L. and Smith, D. A. R.

"CHARACTERISATION AND MODIFICATION OF A VORTEX WAKE IN THE NEAR FIELD"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

The most attractive alleviation method from an operational point of view is to employ active or passive devices on the aircraft to hasten wake destruction, enabling a blanket decrease in aircraft separation. Premature destruction of the wake can be brought about by exciting co-operative instabilities, first described by Crow which amplify under mutual inductance of the vortex pair or pairs and lead to linking of the vortices, formation of vortex rings and subsequently a benign wake. These instabilities are naturally excited by atmospheric turbulence; however, the amplification rates are slow and the distance for the wake to become benign can be hundreds of spans. By forcing these instabilities by devices on the wing we seek to significantly reduce this distance. In this preliminary study a small wind tunnel, 0.45m x 0.3m test section, is used to study the wake from half span NACA 0012 models in the very near field. By using this modest facility, methods for perturbing the vortex, which are ineffective, can be quickly discounted. If a perturbation does not persist in the near-field then it is very unlikely there will be any far field effect either. Planer measurements and velocity profiles through the center of the vortex from a variety of half span-models have been made. These confirmed that the vortex core is formed from the separated flow around the tip and the subsequent roll up of the shear layer from the trailing edge is of secondary importance. This justified the use of short span, large chord wings which from a practical point of view allows easier incorporation of means for perturbing the vortex, i.e. air supplies. Two perturbation schemes are presented. The first is blowing axially into the vortex from a jet just inboard of the wing tip. The second perturbation scheme was to use pulsed span-wise jets in the wing tip to deflect the vortex formation outboard. PIV results showed that the vortex position could be oscillated with significant amplitude at the Crow instability frequency for this set-up. As such, this method shows promise for seeding instability in multiple vortex wakes and could equally be applied to flap edges.

Heyes, A. L., Hubbard, S. J., Marquis, A. J. and Smith, D. A.

"ON THE ROLL-UP OF A TRAILING VORTEX SHEET IN THE VERY NEAR FIELD"

Proc. IMechE, Vol. 217, Part G, 2003, pp. 263-269.

This paper addresses a discrepancy found between the rate of roll-up of a trailing vortex sheet calculated from point vortex simulations and that from measured data. Measurements of the wake behind a rectangular planform NACA 0012 section wing at 7.5 deg angle of attack show that some 50 per cent of the circulation in the wake is already present in the vortex core or 'rolled-up region' at the trailing edge of the wing, and that there is no increase in the circulation contained within this region

within one chord length downstream of the trailing edge. This conflicts with two-dimensional point vortex simulations of sheet roll-up which predict no initial core at the trailing edge and a constantly increasing value of circulation in the vortex in the downstream direction. A modification to include the effect of the tip vortex in the simulation is proposed and is shown to represent the behavior of the vortex sheet in the very near field accurately.

Heyes, A. L., Jones, R. F. and Smith, D. A. R.

"WANDERING OF WING-TIP VORTICES"

The Calouste Gulbenkian Foundation, 12th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 2004

Vortex wakes are an example of flows which exhibit unsteadiness from sources other than turbulence. The phenomenon of vortex wandering is where the vortex core moves in an apparently random fashion relative to the fixed observer. This prevents reliable conclusions from being drawn from temporally averaged measurements which, for example, reduces their value for CFD validation unless its effects are dealt with. Previous studies have demonstrated possible strategies to extract reliable data from that affected by wandering, but the methods used are not necessarily universal or convenient. In this study we demonstrate a relatively simple method for recovering the vortex structure from flow-field data taken using PIV and compare with a statistically based method for carrying out the same. Data is presented showing that wandering amplitude increases linearly with stream-wise distance, and also increases with background turbulence intensity, but decreases with vortex strength. Reliable data, corrected for the effects of wandering, shows that the vortex studied here grows at a more rapid rate than a Lamb-Oseen vortex undergoing viscous diffusion.

Heyson, H. H.

"SOME WAKE-RELATED OPERATIONAL LIMITATIONS OF ROTORCRAFT"

NASA TM-81920, December 1980, NASA Langley Research Center, Hampton, VA

Wind tunnel measurements show that the wake of a rotor, except at near hovering speeds, is not like that of a propeller. The wake is more like that of a wing except that, because of the slow speeds, the wake velocities may be much greater. The helicopter can produce a wake hazard to following light aircraft that is disproportionately great compared to an equivalent fixed wing aircraft. This hazard should be recognized by both pilots and airport controllers when operating in congested areas. Ground effect is generally counted as a blessing since it allows overloaded takeoffs; however, it also introduces additional operation problems. These problems include premature blade stall in hover, settling in forward transition, shuddering in approach to touchdown and complications with yaw control. Some of these problems were treated analytically in an approximate manner and reasonable experiment agreement was obtained. An awareness of these effects can prepare the user for their appearance and their consequences.

Hiejima, T.

"STABILITY OF COMPRESSIBLE STREAMWISE VORTICES"

Physics of Fluids, Vol. 27, 2015, pp. 074107-1 to 074107-10.

A sufficient condition for instability of full compressible inviscid streamwise vortices has been derived using asymptotic analysis with large wavenumbers. Based on the nature of instability, the obtained growth rate is described using an entropy instability term, a spiral instability term, a helicity instability term, and an acoustic instability term. The entropy instability term correlates with compressibility. The spiral instability term is reasonably expressed by the axial and azimuthal velocities and their wavenumbers. The helicity instability term depends on the helicity profiles. In particular, the unstable condition for wake-type flows is satisfied when they possess a negative helicity in the profiles. The acoustic instability term depends on the local speed of sound. Linear and nonlinear numerical simulations are used to validate the instability conditions. The effect of the helicity instability is shown to be significantly strong by the simulations.

Hiejima, T.

"STREAMWISE VORTEX BREAKDOWN IN SUPERSONIC FLOWS"

Physics of Fluids, Vol. 29, 2017, pp. 054102-1 to 054102-13.

Transition processes in supersonic streamwise vortices with wake flows are numerically simulated for Mach numbers from 1.5 to 5.0. This paper discusses the effect of an axial velocity deficit on the breakdown for a fixed small swirl number. For the evolution of the linear unstable mode at Mach 2.5, although the linear-growth range is short, the eigenfunction profiles of the mode resolved from a numerical simulation are generally consistent with those obtained from the linear stability analysis. For the discovery of the supersonic vortex breakdown, when the deficits are large within Mach number 2.5, spiral breakdowns occur with the azimuthal wavenumber.

Hiejima, T.

"EFFECTS OF STREAMWISE VORTEX BREAKDOWN ON SUPERSONIC COMBUSTION"

Physical Review E, Vol. 93, 2016, pp. 043115-1 to 043115-15.

This paper presents a numerical simulation study of the combustion structure of streamwise vortex breakdown at Mach number 2.48. Hydrogen fuel is injected into a combustor at sonic speed from the rear of a hyper-mixer strut that can generate streamwise vortices. The results show that the burning behavior is enhanced at the points of the shock waves that are incident on the vortex and therefore the vortex breakdown in the subsonic region occurs due to combustion. The breakdown domain in the mainstream is found to form a flame-holding region suited to combustion and to lead to a stable combustion field with detached flames. In this way, streamwise vortex breakdown has an essential role in combustion enhancement and the formation of flames that hold under supersonic inflow conditions. Finally, the combustion property defined here is shown to coincide with the produced-water mass flow.

This property shows that the amount of combustion is saturated at equivalence ratios over 0.4, although there is a slight increase beyond 1.

Hiejima, T.

"LINEAR STABILITY ANALYSIS ON SUPERSONIC STREAMWISE VORTICES"

Physics of Fluids, Vol. 25, 2013, pp. 114103-1 to 114103-17.

In this study, the spatial growth rates of supersonic streamwise vortices were investigated by inviscid linear stability analysis. The freestream Mach numbers were 2.5, 5.0, and 7.5. In previous measurements taken to define the streamwise vortices, the stagnation temperature profile of supersonic flows is approximately uniform. This study found that the growth rate of vortices at the uniform stagnation temperature is smaller than that of isentropic vortices. The instability properties of the streamwise vortices can be explained by the ratio of the circulation to the axial velocity deficit, and by the Mach number. Moreover, it is found that the compressibility effect, by which the instability reduces as the Mach number increases, is caused by the negative energy arising from the entropy gradient of supersonic vortices that accompanies the axial velocity deficit-like wake. From an energy perspective, the effect may reasonably be correlated with the large density perturbations in supersonic flows. This study also proposes a general convective Mach number for supersonic streamwise vortices. The normalized growth rates are shown to be a function of convective Mach number within the investigated range of ratio parameters.

Hiejima, T.

"ONSET CONDITIONS FOR VORTEX BREAKDOWN IN SUPERSONIC FLOWS"

Journal of Fluid Mechanics, Vol. 840, 2018, pp. R1-1 to R1-12.

This study proposes an onset condition of shock-free supersonic vortex breakdown from the axial momentum variation, which applies in the presence or absence of a stagnation point. The condition is derived from a comprehensive approach to vortex breakdown. Supersonic breakdown appeared when the swirl parameter and Mach number were small. Moreover, bubble-type breakdowns with a stagnation point, which occur in subsonic conditions, could not occur under the supersonic condition in the present analysis. The predicted breakdowns under this condition were consistent with the results of the three-dimensional numerical simulations for Mach numbers ranging from 1.5 to 5.0. Supersonic vortex breakdowns were clearly captured by the helicity contours in the numerical results. The threshold of the downstream Mach number required for spiral breakdown with no stagnation point was also theoretically derived and verified in numerical results. These findings provide new insights into vortex breakdown in supersonic flows.

Hiejima, T.

"SPATIAL EVOLUTION OF SUPERSONIC STREAMWISE VORTICES"

Physics of Fluids, Vol. 26, 2014, pp. 074102-1 to 074102-19.

In this paper, the spatial developments of high Mach number streamwise vortices have been investigated using direct numerical simulations for Mach numbers from 2.5 to 9.0. The particular streamwise vortices studied here are those with uniform stagnation temperatures and those with constant entropy. For vortices with uniform stagnation temperature, the calculated spatial evolutions show that for small swirl parameters, a bending wave mode is excited and spiral structures of low-wavenumber modes only develop downstream. In contrast, for swirl parameters larger than a moderate amount (approximately 0.5), relaminarization occurs downstream. This study also found that the relation between the circulation and the freestream Mach number contributes to a necessary condition as to whether perturbations can grow in supersonic flows. For isentropic streamwise vortices, instability properties at high Mach numbers parallel those in low-speed flows because the evolution can give rise to high-wavenumbers within the core. The resulting entropy instability is analogous to the Rayleigh-Taylor instability and has the advantage of being insensitive to compressibility effects in supersonic flows.

Hiering, W. A. and Ahlers, R. H.

"EVALUATION OF THE WAKE OF AN S-58 HELICOPTER"

Final Report, Project No. 348-011-01V, July 1963, Federal Aviation Agency, Atlantic City, NJ

A brief exploratory study of air movements near the ground within the wake generated by a 12,000-pound Sikorsky S-58 helicopter was conducted under conditions of light and moderate winds. Windspeed instrumentation was used to measure wake speeds in a plane approximately perpendicular to the test site surface wind. The smoke patterns induced by the wake were photographed in color and were used as the basis for correlation of wake speed data. The highest wake velocities occurred during hovering flight. The wake generated by the hovering helicopter contacted the ground quickly, expanded outward from the hover center upon ground contact and exhibited rapid growth - hence rapid wake speed deterioration - and the spreading portions were contained within 20 feet of the ground. Although the wake speeds produced during forward flight were not as high as those produced in hover flight, they persisted in the air mass for a much greater time. Also, the speed of travel of the wake system toward the ground decreases as the helicopter forward speed increases. These wakes with their vortices drifted downward approximately at wind speed. The maximum propagation of wake velocities upwind was approximately 85 feet.

Higuchi, H., Goto, Y., Hiramoto, R. and Meisel, I.

"ROTATING FLYING DISKS AND FORMATION OF TRAILING VORTICES"

AIAA Paper No. 2000-4001, Denver, CO, August 2000

An experimental investigation on the flow past a flying disk is carried out in a low-speed wind tunnel. Using flow visualization techniques supplemented by Digital Particle Image Velocimetry (PIV), detailed flow characteristics depicting the trailing vortices, boundary layer separation and wake structure are

obtained. Effects of disk rotation on the boundary layer transition and separation are studied. Results indicate that the effect of rotation on the vortex strength becomes negligible at high angles of attack. At low lifting conditions of the present configuration, the rotation suppresses the boundary layer separation near the trailing edge and increases the downwash. In the intermediate angles, however, the leading-edge separation bubble is affected by the rotation. The flow transition over the advancing surface is also noted.

Higuchi, H., Quadrelli, J. C. and Farell, C.

"VORTEX ROLL-UP FROM AN ELLIPTIC WING AT MODERATELY LOW REYNOLDS NUMBERS"

AIAA Journal, Vol. 25, No. 12, December 1987, pp. 1537-1542

An experimental investigation of tip-vortex roll-up was undertaken at moderately low Reynolds numbers for an elliptic wing with a NACA 66-2-415 section. Flow visualizations and laser Doppler velocimetry measurements were carried out to examine the flow in the vortex core and the tangential velocity distributions around the core. Separation was observed on both sides of the foil for Reynolds numbers up to 5×10^5 . The observed changes in the location of separation and reattachment with angle of attack and Reynolds number were adequately predicted by laminar boundary-layer calculations. Axial and tangential velocity profile measurements were made at Reynolds numbers up to 5×10^4 . The vortex core radius was found to grow with increasing angle of attack, increasing downstream distance, and decreasing Reynolds number. A comparison of the experimentally determined velocity distributions and core sizes, with results of inviscid, laminar, and turbulent vortex models, is presented.

Hill, C.

"MODERN FIBRE-OPTIC COHERENT LIDARS FOR REMOTE SENSING"

Proceedings SPIE DLC590, Paper 9649-23, Remote Sensing and Security, September 2015.

This paper surveys some growth areas that exploit near-IR coherent laser sources and fiber-optic hardware from the telecoms industry. Advances in component availability and performance are promising benefits in several military and commercial applications. Previous work has emphasized Doppler wind speed measurements and wind/turbulence profiling for air safety, with recent sharp increases in numbers of lidar units sold and installed, and with wider recognition that different lidar/radar wavebands can and should complement each other. These advances are also enabling fields such as micro-doppler measurement of sub-wavelength vibration and acoustic waves, including non-line-of-sight acoustic sensing in challenging environments. To shed light on these different applications we review some fundamentals of coherent detection, measurement probe volume, and parameter estimation -- starting with familiar similarities and differences between 'radar' and 'laser radar.' The consequences of changing the operating wavelength by three or four orders of magnitude -- from millimetric or centimetric radar to a typical fibre-optic lidar working near 1.5 microns -- need regular review, partly because of continuing advances in telecoms technology and computing.

Hill, C., Bennett, J. and Smith, D.

"AIRPORT TRIALS WITH THE AVIATION ZEPHIR WIND LIDAR"

15th Coherent Laser Radar Conf., Toulouse, France, June 2009.

QinetiQ's ZephIR is a conical-scan coherent Doppler lidar operating eye-safe near 1.5 microns, typically providing five-height wind speed profiles up to 150 m, updated once or twice per minute. More than 50 units are installed worldwide for applications including meteorology, wind farm assessment, and wind turbine studies. QinetiQ has recently fielded a modified version 'Aviation ZephIR' using results within a single one-second scan to estimate the wind speed, and also to detect the presence of turbulence and wake vortices. Over a few consecutive scans, the vortices can be tracked as they descend and are blown by the local wind. Aviation ZephIR senses a small, possibly critical, volume of air -- for example the critical airport regions where takeoff and landing -- for real-time, low-altitude, wind profiling and gust warning at airports. We have deployed at Birmingham International Airport (where most aircraft are light or medium) and at London Heathrow Airport (used by many large Airbus and Boeing aircraft, and by the Airbus A380). We present results on wind profiles, vortex detection, and vortex tracks.

Hill, D. J.

"PART I. VORTEX DYNAMICS IN WAKE MODELS. PART II. WAVE GENERATION"

PhD Thesis, May 1998, California Institute of Technology, Pasadena, CA.

In Part I, steady wakes in inviscid fluid are constructed and investigated using the techniques of vortex dynamics. As a generalization of Foppi's flow past a circular cylinder, a steady solution is given for flow past an elliptical cylinder of arbitrary aspect ratio (perpendicular or parallel to the flow at infinity) with a bound wake of two symmetric recirculating eddies in the form of a point vortex pair. Linear stability analysis predicts an asymmetric instability and the symmetric nonlinear evolution is discussed in terms of a Kirchhoff-Routh path function. The wake behind a sphere is represented by a thin cored vortex ring of arbitrary internal structure. Steady configurations are obtained and long-wavelength perturbations to the ring centerline identify a tilting instability. A generalization of the Kirchhoff Routh function to an axisymmetric flow consisting of vortex rings and a body is presented. Using conformal maps and point vortices, translating symmetric two-dimensional bubbles with a vortex pair wake are constructed. An instability in which the bubble and vortex pair tilt away from each other is found as well as a symmetric oscillatory instability. The cross-section of a trailing vortex pair immersed in a cross-stream shear is represented by two counter-rotating vortex patches. Numerical and analytical analyses are provided. The method of Schwarz functions as introduced by Meiron, Saffman, and Schatzman is used in the computation and stability analysis of steady patch shapes. Excellent agreement is obtained using an elliptical patch model. An instability essentially isolated to a single patch is identified, the nonlinear evolution of the elliptical patch model suggests that the patch whose fluid elements rotate against the shear will be destroyed. Part II examines a possible mechanism for the generation of water waves which arises from the instability of an initially planar free surface in the presence of a parallel, sheared,

inviscid flow. A two-dimensional steady flow comprised of exponential profiles representing both wind and a drift layer in the water is infinitesimally perturbed. The resulting Rayleigh equation is analytically solved by means of Hyper-geometric functions and the dispersion relation is implicitly defined as solutions of a transcendental equation; stability boundaries are determined and growth rates are calculated. Comparisons are made with the simpler model of Caponi et al. which uses piecewise linear profiles.

Hill, D. J. and Saffman, P. G.

"COUNTER-ROTATING VORTEX PATCHES IN SHEAR: A MODEL OF THE EFFECT OF WIND SHEAR ON AIRCRAFT TRAILING VORTICES"

Proceedings of the Royal Society of London, Series A, Vol. 458, May 2002, pp. 1527-1553

The shape and stability of two-dimensional, uniform patches of vorticity in incompressible inviscid fluid are calculated. The object of the study is to investigate the effect of wind shear on trailing vortices. The wind shear is modelled by simple shear with velocities in the plane perpendicular to the trailing vorticity. The first portion of this study models the trailing vortices as a pair of uniform straight counter-rotating line vortices which are essentially point vortices. They move under their self-induced velocities and the external shear. It is shown that the equations for the positions of the vortices can be solved exactly, and they move on parabolic trajectories with the horizontal and vertical separations kept constant. The trajectories are weakly unstable: infinitesimal disturbances grow algebraically in time. But, apart from the effect of wind shear on the horizontal displacement and an asymmetry of the streamlines, wind shear has no significant effect on the motion of the vortex pair under the point vortex approximation. The situation is different when the finite size of the trailing-vortex cores is taken into account. It is found that the vortex patches may be deformed significantly, or very slightly, depending upon the sense of rotation of the trailing vortex relative to the sense of rotation in the external simple shear. When co-rotating the patch remains circular to a good approximation, as would a single co-rotating patch in a uniform shear, a case which can be solved exactly. But when counter-rotating, the patch may be significantly deformed into a long, thin shape, perpendicular to the line joining the centroids of the patches.

Hill, F. M.

"A NUMERICAL STUDY OF THE DESCENT OF A VORTEX PAIR IN A STABLY STRATIFIED ATMOSPHERE"

J. Fluid Mech., Vol. 71, Part 1, September 1975, pp. 1-13

Numerical methods are used to investigate the motion of a horizontal vortex pair through a stably stratified atmosphere. The vortices carry with them a mass of fluid whose density differs from that of the air through which it descends, and the surface of this accompanying fluid becomes a vortex sheet, which is modelled by a set of discrete line vortices. It is shown that, at first, the vortex pair slows down with the shape of the envelope of the accompanying fluid remaining constant. Later, vorticity

concentrates at the rear, initiating detrainment and causing a downward acceleration of the vortex pair. Throughout the motion, the vortices approach each other.

Hill, M. A. and Haering Jr, E. A.

"FLOW VISUALIZATION OF AIRCRAFT IN FLIGHT BY MEANS OF BACKGROUND ORIENTED SCHLIEREN USING CELESTIAL OBJECTS"

AIAA Paper 2017-3553, June 2017, Denver, CO.

The Background Oriented Schlieren using Celestial Objects series of flights was undertaken in the spring of 2016 at the National Aeronautics and Space Administration Armstrong Flight Research Center to further develop and improve a flow visualization technique which can be performed from the ground upon flying aircraft. Improved hardware and imaging techniques from previous schlieren tests were investigated. A United States Air Force T-38C and NASA B200 King Air aircraft were imaged eclipsing the sun at ranges varying from 2 to 6 nautical miles, at subsonic and supersonic speeds. Images were post-processed using the Background Oriented Schlieren technique with optical flow algorithms to reveal both subsonic and supersonic flow features around the aircraft. The resulting imaging hardware and techniques demonstrated its applicability as a mature instrumentation system for performing flow visualization on vehicles in flight.

Hind, M. D., Holmes, M. J. and Naughton, J. W.

"EXPERIMENTAL INVESTIGATION OF TURBULENT SWIRLING WAKES"

AIAA Paper 2014-0958, January 2014, National Harbor, MD.

The swirling wake has been studied experimentally. A specialized swirling wake generator was developed that introduced a minimal number of artifacts to the flow. Particle Image Velocimetry was used to capture the wake flow-field. The results show that, although the swirling wakes were deeper initially, they decay faster than their non-swirling counterpart. The implications of this study are important. The range studied here was the near field (x/D less than 10), but this is more than the typical spacing between wind turbines constructed in arrays. As such, it indicates that capturing the effects of the curvature on the turbulence in these wakes is critical if the wake behavior is to be adequately captured. Since small increases in energy capture by a wind turbine translates into a significant decrease to the cost of energy, further investigation of the effects of swirl on wake behavior are warranted. In addition to this practical application, the large effect of swirl on wake behavior suggests that the swirling wake is a good case for investigating the effect of swirl on turbulence. In addition to the mean flow quantities, the swirling jet could be used to understand changes in the turbulence structure and the related change in turbulence structure. Such information would add to the understanding of the general case of turbulent flows with significant curvature that are widely found in real-world applications.

Hinton, D. A.

"DEVELOPMENT OF AN INTEGRATED WAKE VORTEX SPACING SYSTEM"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

A wake vortex spacing system has been developed to prescribe safe aircraft separation criteria at major airports. The Aircraft Vortex Spacing System (AVOSS) integrates the output of several systems to produce weather-dependent, dynamic wake vortex spacing criteria. These systems provide current and predicted (nowcast) weather conditions above the surface, models of wake vortex transport and decay in these weather conditions, and real-time feedback of wake vortex behavior from sensors. A version of AVOSS, suitable for concept demonstration, has been constructed and tested at the Dallas-Fort Worth International Airport and will be demonstrated to the aviation industry in late 2000. The demonstration is of concept feasibility, and additional effort is required to deploy an operational system for actual aircraft spacing reduction. Initial tests with the AVOSS system verify the potential to increase runway arrival rates by 10 to 15% in the first intended application of the system, reduced spacing in-trail to a single runway. The system technology may also be applied to other applications, such as enabling closely-spaced approaches to parallel runways, where the capacity gains may potentially be greater. This paper describes the AVOSS system architecture, subsystem capabilities, and results from a system deployment at DFW in the fall of 1999.

Hinton, D. A.

"DESCRIPTION OF SELECTED ALGORITHMS AND IMPLEMENTATION DETAILS OF A CONCEPT-DEMONSTRATION AIRCRAFT VORTEX SPACING SYSTEM (AVOSS)"

NASA TM 2001-211027, June 2001, NASA Langley Research Center, Hampton, VA

A ground-based system has been developed to demonstrate the feasibility of automating the process of collecting relevant weather data, predicting wake vortex behavior from a data base of aircraft, prescribing safe wake vortex spacing criteria, estimating system benefit, and comparing predicted and observed wake vortex behavior. This report describes many of the system algorithms, features, limitations, and lessons learned, as well as suggested system improvements. The system has demonstrated concept feasibility and the potential for airport benefit. Significant opportunities exist however for improved system robustness and optimization. A condensed version of the development lab book is provided along with samples of key input and output file types. This report is intended to document the technical development process and system architecture, and to augment archived internal documents that provide detailed descriptions of software and file formats.

Hinton, D. A.

"AIRCRAFT VORTEX SPACING SYSTEM (AVOSS) CONCEPT AND DEVELOPMENT"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 11-22

The goal of the Aircraft Vortex Spacing System (AVOSS) effort is to support the Terminal Area Productivity program goal of improving airport capacity during instrument operations to capacity levels comparable to current visual operations. The AVOSS system concept is to combine meteorological information, wake vortex prediction, and wake sensors into an integrated system that advises the ATC system of the wake vortex spacing required for avoidance of wake turbulence. This task is accomplished by establishing a safety corridor from the glide slope intercept point to the landing runway, then using ambient and forecast atmospheric state to predict the time required for wake vortices to clear the corridor or decay. Statistical meteorological data is used to estimate the uncertainty in the wake predictions in order to provide spacing recommendations that will be safe and usable for a significant time period. The technical challenges of the program include the ability to sense and predict atmospheric state variables, the ability to predict wake motion and decay in a range of conditions, and system performance and costs that permit a return on the installation investment. The product of the AVOSS project will be a demonstration of a system architecture and data to support sensor selection and benefit/cost tradeoff studies.

Hinton, D. A.

"WAKE VORTEX SENSORS REQUIREMENTS OVERVIEW"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 228-234

The role of wake vortex sensors within an automated wake vortex spacing system is to provide a safety monitor function by validation of predictions of wake vortex residence time in the safety corridor. This requires not only that wakes be detected, but also that the wakes be tracked until they have departed the corridor or have decayed to circulation values that are no longer an operational impact to following aircraft. Specific sensor requirements are likely to evolve in three phases. Sensors required for the AVOSS development program have minimal reliability, automation, or all-weather needs, but must provide high resolution wake data to support research efforts. Sensors required for an operational test bed will require much greater reliability, self-monitoring, and automation, as well as the ability to cover multiple locations on the approach path. Sensors in an operational system will require very high reliability and automation, but potentially low resolution of wake velocity profiles. The sensors must accommodate real-world constraints such as siting limitations, no adverse environmental impacts, detection of wakes that return to the corridor after leaving, discrimination of simultaneous presence of wakes from multiple aircraft, and tracking wakes in ambient turbulence and shear. Analysis of airport climatological data suggests that even sensors limited by cloud or low visibility may provide the necessary function in a large percentage of the conditions that require instrument approaches.

Hinton, D. A.

"AVOSS DEVELOPMENT APPROACH"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 460-468

The AVOSS development activity will provide for a field demonstration of the AVOSS concept. During the demonstration all required AVOSS subsystems will be deployed and operating in real-time as part of an integrated system. Outputs of the AVOSS system will not be provided to Air Traffic Control as part of this program, and no aircraft separations will be altered because of the AVOSS tests. The objective of the full-scale demonstration is to aggressively integrate the required system technologies, determine the utility and limitations of the currently existing state of the art in meteorological and wake prediction systems, and focus the research activities for maximum payoff. A facility is being established at the Dallas-Fort Worth airport to provide dedicated meteorological sensors, wake vortex sensors, and networks for system testing. The network will integrate atmospheric data from acoustic sodars, a radar profiler with Radio Acoustic Sounding System, a 150-foot meteorological tower, and products available from the Integrated Terminal Weather System (ITWS) test bed. A pulsed wake tracking lidar deployed by NASA Langley, a continuous wave wake tracking lidar deployed by MIT Lincoln Laboratory, and a ground wind line deployed by the Volpe National Transportation Systems Center are also interfaced to the network for automatic transfer of wake track data to AVOSS. This facility will be used for system integration, testing new wake and system algorithms, and AVOSS performance assessment.

Hinton, D. A.

"AIRCRAFT VORTEX SPACING SYSTEM (AVOSS) CONCEPTUAL DESIGN"

NASA TM-110184, August 1995, NASA Langley Research Center, Hampton, VA

A concept is presented for the development of a prototype Aircraft Vortex Spacing System (AVOSS). The AVOSS development is being performed by NASA Langley as an element of the Terminal Area Productivity (TAP) Program, and in support of the FAA integrated Wake Vortex Program Plan. The purpose of the AVOSS is to provide dynamical, weather dependent wake vortex separation criteria to ATC facilities with adequate stability and lead time for use in runway scheduling. The AVOSS will accomplish this task through a combination of wake vortex transport and decay predictions, weather state knowledge, defined aircraft operational procedures and corridors, and wake vortex safety sensors. With the appropriate interface to planned ATC automation, spacing can be tailored to specific generator/follower aircraft types rather than several broad weight categories of aircraft. In a manual ATC environment, the AVOSS may be used to determine when reduced separation standards may be used. Work is currently underway to address the critical disciplines and knowledge needs to demonstrate a prototype AVOSS in the 1999 time-frame. This document describes the concept and candidate form of an operational AVOSS system, system ground rules and requirements, research needs, and the development efforts being followed.

Hinton, D. A.

"AN AIRCRAFT VORTEX SPACING SYSTEM (AVOSS) FOR DYNAMICAL WAKE VORTEX SPACING CRITERIA"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 23-1 to 23-12

A concept is presented for the development and implementation of a prototype Aircraft Vortex Spacing System (AVOSS). The purpose of the AVOSS is to use current and short-term predictions of the atmospheric state in approach and departure corridors to provide, to ATC facilities, dynamical weather dependent separation criteria with adequate stability and lead time for use in establishing arrival scheduling. The AVOSS will accomplish this task through a combination of wake vortex transport and decay predictions, weather state knowledge, defined aircraft operational procedures and corridors, and wake vortex safety sensors. Work is currently underway to address the critical disciplines and knowledge needs so as to implement and demonstrate a prototype AVOSS in the 1999/2000 time-frame.

Hinton, D. A. and Charnock, J. K.

"AIRCRAFT VORTEX SPACING SYSTEM CURRENTLY UNDER DEVELOPMENT WOULD SAFELY INCREASE RUNWAY CAPACITY"

ICAO Journal, Vol. 53, No. 7, September 1998, pp. 14-17, 28

Researchers are at work developing technology needed to support an aircraft vortex spacing system that adjusts separation from wake vortices according to weather conditions. Recent studies have examined aircraft responses to wake encounters and assessed wake strength, and an AVOSS system demonstration is planned at a major airport in 2000.

Hinton, D. A. and O'Connor, C. J.

"DEVELOPMENT OF A WAKE VORTEX SPACING SYSTEM FOR AIRPORT CAPACITY ENHANCEMENT AND DELAY REDUCTION"

Proceedings of the 19th IEEE Digital Avionics Systems Conference, Vol. 1, October 2000, pp. 3E6-1-3E6-10

The Terminal Area Productivity project has developed the technologies required (weather measurement, wake prediction, and wake measurement) to determine the aircraft spacing needed to prevent wake vortex encounters in various weather conditions. The system performs weather measurements, predicts bounds on wake vortex behavior in those conditions, derives safe wake spacing criteria, and validates the wake predictions with wake vortex measurements. System performance to date indicates that the potential runway arrival rate increases with AVOSS, considering common path effects and ATC delivery variance, is 5% to 12% depending on the ratio of large and heavy aircraft. The concept demonstration system, using early generation algorithms and minimal optimization, is performing the wake predictions with adequate robustness such that only 4 'hard exceedances' have been observed in 1235 wake validation cases. This performance demonstrates the feasibility of predicting wake behavior bounds with multiple uncertainties present, including the unknown aircraft weight and speed, weather persistence between the wake prediction and the

observations and the location of the weather sensors several kilometers from the approach location. A concept for the use of the AVOSS system for parallel runway operations has been suggested, and an initial study at the JFK International Airport suggests that a simplified AVOSS system can be successfully operated using only a single lidar as both the weather sensor and the wake validation instrument. Such a self-contained AVOSS would be suitable for wake separation close to the airport, as is required for parallel approach concepts such as SOIA.

Hinton, D. A. and Tatnall, C. R.

"A CANDIDATE WAKE VORTEX STRENGTH DEFINITION FOR APPLICATION TO THE NASA AIRCRAFT VORTEX SPACING SYSTEM (AVOSS)"

NASA TM-110343, September 1997, NASA Langley Research Center, Hampton, VA

A significant effort is underway at NASA Langley to develop a system to provide dynamical aircraft wake vortex spacing criteria to Air Traffic Control (ATC). The system under development, AVOSS, combines the inputs of multiple subsystems to provide separation matrices with sufficient stability for use by ATC and sufficient monitoring to ensure safety. The subsystems include a meteorological subsystem, a wake behavior prediction subsystem, a wake sensor subsystem, and system integration and ATC interfaces. The proposed AVOSS can use two factors, singly or in combination, for reducing in-trail spacing. These factors are wake-vortex motion out of a predefined approach corridor and wake decay below a strength that is acceptable for encounter. Although basic research into the wake phenomena has historically used wake total circulation as a strength parameter, there is a requirement for a more specific definition that may be applied across multiple disciplines and teams to produce a real-time, automated system. This paper presents some of the limitations of previous applications of circulation to aircraft wake observations and describes the results of a preliminary effort to bound a spacing system strength definition.

Hinton, D. A., Charnock, J. K. and Bagwell, D. R.

"DESIGN OF AN AIRCRAFT VORTEX SPACING SYSTEM FOR AIRPORT CAPACITY IMPROVEMENT"

AIAA Paper No. 2000-0622, Reno, NV, January 2000

The National Aeronautics and Space Administration (NASA) is addressing airport capacity enhancements through the Terminal Area Productivity (TAP) program. Within TAP, the Reduced Spacing Operations element at the NASA Langley Research Center is developing an Aircraft Vortex Spacing System (AVOSS). AVOSS will integrate the output of several systems to produce weather dependent, dynamic wake vortex spacing criteria. These systems provide current and predicted weather conditions, models of wake vortex transport and decay in these weather conditions, and real-time feedback of wake vortex behavior from sensors. The goal of the NASA program is to provide the research and development to demonstrate an engineering model AVOSS, in real-time operation, at a major airport. A wake vortex system test facility was established at the Dallas-Fort Worth International Airport (DFW) in 1997 and tested in 1998. Results from operation of the initial AVOSS system, plus

advances in wake vortex prediction and near-term weather forecast models, 'nowcast', have been integrated into a second-generation system. This AVOSS version is undergoing final checkout in preparation for a system demonstration in 2000. This paper describes the revised AVOSS system architecture, subsystem enhancements, and initial results with AVOSS version 2 from a deployment at DFW in the fall of 1999.

Hinton, D. A., Charnock, J. K., Bagwell, D. R. and Grigsby, D.

"NASA AIRCRAFT VORTEX SPACING SYSTEM DEVELOPMENT STATUS"

AIAA Paper No. 1999-0753, Reno, NV, January 1999

The National Aeronautics and Space Administration (NASA) is addressing airport capacity enhancements during instrument meteorological conditions through the Terminal Area Productivity (TAP) program. Within TAP, the Reduced Spacing Operations sub-element at the NASA Langley Research Center is developing an Aircraft Vortex Spacing System (AVOSS). AVOSS will integrate the output of several systems to produce weather dependent, dynamic wake vortex spacing criteria. These systems provide current and predicted weather conditions, models of wake vortex transport and decay in these weather conditions, and real-time feedback of wake vortex behavior from sensors. The goal of the NASA program is to provide the research and development to demonstrate an engineering model AVOSS in real-time operation at a major airport. The demonstration is only of concept feasibility, and additional effort is required to deploy an operational system for actual aircraft spacing reduction. This paper describes the AVOSS system architecture, a wake vortex facility established at the Dallas-Fort Worth International Airport (DFW), initial operational experience with the AVOSS system, and emerging considerations for subsystem requirements. Results of the initial system operation suggest a significant potential for reduced spacing.

Hiremath, B. M., Holla, V. S. and Govindaraju, S. P.

"STUDY OF FLOW FIELD IN THE NEAR WAKE OF DELTA WINGS"

Journal of the Aero. Society of India, Vol. 36, No. 1, February 1984, pp. 17-27.

An experimental study of vortex flow field on as well as in the near wake of a plane delta wing with sharp leading edges is presented. Complete velocity measurements in this three-dimensional flow field are obtained by means of a blunt conical nosed five-hole probe. The probe is mounted on a traversing mechanism with three linear degrees of freedom and the probe is pre-calibrated for yaw and pitch. The vortex core location is also measured by total head survey using a Kiel tube. The results plotted in the form of equi-velocity contours as well as cross flow velocity contours at each of the chordwise cross flow planes and in the wake region. Using these plots the vortex core location, its growth and development along the wing and its subsequent motion in the near wake is studied. The experimental data on the vortex core location on the wing surface are found to be in good agreement with the available theoretical data.

Hiremath, B. M., Holla, V. S. and Govindaraju, S. P.

"STUDY OF FLOW FIELD IN THE NEAR WAKE OF DELTA WINGS"

34th Annual Meeting of the Aeronautical Society of India, December 1982, Madras, India.

An experimental study of vortex flow field on as well as in the near wake of a plane delta wing with sharp leading edges is presented. Complete velocity measurements in this three-dimensional flow field are obtained by means of a blunt conical nosed five-hole probe. The probe is mounted on a traversing mechanism with three linear degrees of freedom and the probe is precalibrated for yaw and pitch. The vortex core location is also measured by total head survey using a Kiel tube. The results plotted in the form of equi-velocity contours as well as cross flow velocity contours at each of the chordwise cross flow planes, and also in the wake region. Using these plots the vortex core location, its growth and development along the wing and its subsequent motion in the near wake is studied. The experimental data on the vortex core location on the wing surface are found to be in good agreement with the available theoretical data.

Hirsa, A. H.

"AN EXPERIMENTAL INVESTIGATION OF VORTEX PAIR INTERACTION WITH A CLEAN OR CONTAMINATED FREE SURFACE"

Ph.D. Thesis, January 1990, Univ. of Michigan, Ann Arbor, MI.

The interaction between a pair of trailing vortices and a free surface was studied. The vortices were produced by a submerged delta wing and a negative angle of attack. To isolate and study the interaction, an apparatus was built to generate reproducible vortex pairs with the same Reynolds number and Froude number as the trailing vortices. The apparatus consisted of a pair of counter rotating flaps which were moved by a computer-controlled stepping motor. The vortex pairs generated with the flaps were laminar and remained laminar during the time that significant interaction with the free surface was observed. The Froude number for the vortices was low and the resulting surface deformations were small. Particle image velocimetry along with flow visualization were used to study the flow field. Striations were also observed during the interaction of the vortex pair with the free surface. The striations were found to be caused by cross-stream vortices which are stretched by the strain field between the trailing vortices and their images. Contaminants on the free surface were found to have a large influence on both the free surface deformations and the flow field of the vortices. Also, a Reynolds ridge on the free surface was observed on each side of the wake. The effect of surface contamination was studied by adding known amounts of an insoluble surfactant to the free surface. Surface depressions, termed scars, were observed above the primary vortices as well as the secondary vortices, although in the case on the secondary vortices the depression was much greater.

Hirsa, A., Lopez, J. M. and Kim, S.

"EVOLUTION OF AN INITIALLY COLUMNAR VORTEX TERMINATING NORMAL TO A NO-SLIP WALL"

Experiments in Fluids, Vol. 29, 2000, pp. 309-321

The early evolution of an initially columnar vortex normal to a solid wall was examined. The vortex was generated by a pair of flaps in a water tank. Detrimental effects from the wall during the vortex generation were avoided by producing the vortex normal to a free surface and subsequently bringing a horizontal plate into contact with the surface. Digital particle image velocimetry (DPIV) measurements of the velocity and vorticity, together with laser induced fluorescence (LIF) visualizations, in a meridional plane revealed a toroidal structure with the appearance of an axisymmetric vortex breakdown bubble. Agreement was found between the measurements and numerical simulations of the axisymmetric Navier-Stokes equations. The results show that the flow in the effusive corner region is dominated by a Bodewadt-type spatially oscillatory boundary layer within the core region and a potential-like vortex boundary layer at large radius. The toroidal structure results from the interaction between these two boundary layers, leading to the roll up of a dominant shear layer within the Bodewadt structure, and does not develop from the columnar vortex itself.

Hirschel, E. H.

"VORTEX FLOWS: SOME GENERAL PROPERTIES, AND MODELING, CONFIGURATIONAL AND MANIPULATION ASPECTS"

AIAA Paper No. 1996-2514, June 1996, New Orleans, LA.

Properties of vortex flows connected with lifting wings are discussed qualitatively and quantitatively. The concept of 'local vorticity content' of a shear layer is introduced, which results from a Re approaching infinity limiting process. It permits to distinguish kinematically active and inactive vorticity. It is applied to boundary layers, shear layers, etc., and it is shown how the singularities of potential flow theory can be connected to them. The structure of wakes of lifting wings is investigated. Vorticity creation and entropy rise in Euler solutions for lifting wings are explained with the local vorticity content concept. Finally, some vortex-flow manipulation possibilities, which are derived from this concept, are discussed.

Hitzel, S.

"SUB- AND TRANSONIC VORTEX BREAKDOWN FLIGHT CONDITION SIMULATIONS OF THE F-16XL AIRCRAFT"

Journal of Aircraft, Vol. 54, No. 2, March-April 2017, pp. 428-443.

Free-flight Navier-Stokes simulations of the Cranked Arrow Wing Aerodynamics Project International F-16XL aircraft were performed to probe for the complex vortex flow-field structures at high angle of attack close to and beyond vortex breakdown conditions. The scope of the paper probes for the quality and quantity of high-resolution numerical simulations possible with the current computer capacity at free-flight Reynolds numbers. It provides an insight into the effect of turbulence modeling of these complicated flows; the free-flight measured pressure distributions are compared with solutions achieved with the one-equation Spalart-Allmaras turbulence model, the one-equation Spalart-Allmaras

turbulence model with rotation correct, the k-w model, and the turbulence model with scale-adaptive simulation. The third topic of the investigation is the complexity of the vortex flow system of the configuration at sub- and transonic speeds at vortex breakdown conditions. For this purpose, the details of the different vortex systems and their behavior are prepared and discussed.

Hoad, D. J.

"IDENTIFICATION OF METEOROLOGICAL WAKE VORTEX PREDICTORS"

Forecasting Research Technical Report No. 304, March 2000, The Met. Office Aviation Applications Group, Berkshire, UK

Wake vortex safety considerations dictate aircraft separation limits at busy airports. If weather conditions in which wake vortices decay quickly can be identified and used reliably as 'wake vortex predictors', there is potential for making the separation distances dependent on these predictors as well as aircraft weight. This could increase the capacity of airports in certain weather conditions. This study uses the ETWIRL (European Turbulent Wake Incident Reporting Log) database, which contains data for wake vortex incidents reported by the air traffic control (ATC) authority at London Heathrow airport in addition to incidents occurring around the world reported by pilots. In this study, weather data for incidents occurring at Heathrow were extracted from the ETWIRL database and compared with weather data from a 'null incident' database. This 'null incident' database holds weather data from Heathrow airport on days on which no wake vortex incidents were reported by the ATC authority at Heathrow. This comparison identified some weather-related predictors, which could indicate whether a wake vortex incident is likely to occur. A statistical analysis was then performed to analyze the performance of these predictors.

Hoad, D. J.

"IDENTIFICATION OF METEOROLOGICAL WAKE VORTEX PREDICTORS"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

Wake vortex safety considerations currently dictate aircraft separation limits at busy airports. If weather conditions in which wake vortices decay quickly can be identified and used reliably as 'wake vortex predictors', there is potential for making the separation distances dependent on these predictors as well as aircraft weight. This could increase the capacity of airports in certain weather conditions. This study uses the ETWIRL (European Turbulent Wake Incident Reporting Log) database, which contains data for wake vortex incidents reported by the air traffic control (ATC) authority at London Heathrow airport, in addition to incidents occurring around the world reported by airline pilots. Weather data for incidents occurring at Heathrow were extracted from the ETWIRL database and compared with weather data from a 'null incident' database. This null-incident database holds weather data from Heathrow on days on which no wake vortex incidents were reported by the Heathrow ATC authority. This comparison identified some weather-related predictors which could indicate whether a

wake vortex incident is likely to occur. A statistical analysis was then performed to analyze the performance of these predictors, using a wider sample of incident data from the ETWIRL database.

Hoad, D. R.

"HELICOPTER BLADE-VORTEX INTERACTION LOCATIONS -- SCALE-MODEL ACOUSTICS AND FREE-WAKE ANALYSIS RESULTS"

NASA Technical Paper 2658, 1987, Langley Research Center, Hampton, VA.

The results of a model rotor acoustic test in the Langley 4- by 7-Meter Tunnel were used to evaluate a free-wake analytical technique. The acoustic data were examined in detail for blade-vortex interaction acoustic waveform characteristics. These results were used in an acoustic triangulation technique to define the location in the rotor disk of the noise source. These locations along with the results of the free-wake analysis, were used to define the geometry of the blade-vortex interaction phenomena as well as to determine if the free-wake analysis is a capable diagnostic tool. The results of the correlation of the experimentally determined source location and the analytically generated wake geometry for the rectangular blades are encouraging. The free-wake analysis successfully predicts the occurrence of blade-vortex interaction and is able to provide information on the interaction geometry. In the case of the advanced rotor system, the correlation between analysis and experiment is poor. The reason for the poor correlation may be related to the selection of the point on the rotor blade where the vortex is defined as being generated. Additional information is needed to provide a better understanding of the wake geometries developed by nonrectangular rotor blades.

Hoad, D. R., Rhodes, D. B. and Meyers, J. F.

"PRELIMINARY ROTOR WAKE MEASUREMENTS WITH A LASER VELOCIMETER"

NASA-TM-83246, Langley Research Center, Hampton, VA, March 1983.

A laser velocimeter (LV) was used to determine rotor wake characteristics. The effect of various fuselage widths and rotor-fuselage spacings on time averaged and detailed time dependent rotor wake velocity characteristics was defined. Definition of time dependent velocity characteristics was attempted with the LV by associating a rotor azimuth position with each velocity measurement. Results were discouraging in that no apparent time dependent velocity characteristics could be discerned from the LV measurements. Since the LV is a relatively new instrument in the rotor wake measurement field, the cause of this lack of periodicity is as important as the basic research objectives. An attempt was made to identify the problem by simulated acquisition of LV-type data for a predicted rotor wake velocity time history. Power spectral density and autocorrelation function estimation techniques were used to substantiate the conclusion that the primary cause of the lack of time dependent velocity characteristics was the nonstationary flow condition generated by the periodic turbulence level that currently exists in the open throat configuration of the wind tunnel.

Hoeijmakers, H. W. M.

"COMPUTATIONAL AERODYNAMICS OF ORDERED VORTEX FLOWS"

PhD Thesis, May 1989, Technical University of Delft, Delft, The Netherlands.

The physical aspects, the mathematical modeling, and the development and application of computational methods for the simulation of vortical flows are described. The high-Reynolds number vortex flows considered are assumed to be steady, sub-critical and such that the structure of the flow is well-ordered and consists of thin shear layers and slender vortex cores embedded in otherwise irrotational flow. The applications considered are vortex wakes and the flow about three-dimensional (slender) configurations with the flow separating from known separation lines, mostly the sharp leading edges.

Hoeijmakers, H. W. M.

"APPROXIMATE METHOD FOR COMPUTING INVISCID VORTEX WAKE ROLL-UP, PART 2: DESCRIPTION OF COMPUTER PROGRAM VOR2DT"

NLR-TR-85149-U, November 1985, National Aerospace Lab., Amsterdam, Netherland.

In part I of the report, a method is described for approximately computing the shape of steady vortex wakes downstream of aircraft configurations in steady flight through the unsteady analogy. In the analogy the steady fully three-dimensional problem is reduced to a two-dimensional time dependent problem, corresponding to the evolution of a two-dimensional vortex sheet system in successive cross-flow planes. The geometry of the vortex wake in any cross-flow plane consists of independent segments. Each segment is built up out of a continuous vortex sheet and up to two concentrated vortices which model tightly rolled-up vortex cores. Each of the vortices is connected to one of the edges of the continuous vortex sheet. Both single- and double-branched vortices can be accommodated. The method optionally accounts for symmetry and tunnel-wall influence, as well as for cross-flow plane components of the free stream. In part II of the report, the computer program VOR2DT is described in some detail.

Hoeijmakers, H. W. M.

"NUMERICAL SIMULATION OF VORTICAL FLOW"

NLR-MP-86032-U, June 1986, National Aerospace Lab., Amsterdam, Netherlands

Methods are discussed for the numerical simulation of vortical type of flow. The various methods in use at present are discussed in some detail, primarily with a view towards three-dimensional steady flow applications such as vortex wakes and leading-edge vortex flows. Some of the computational aspects of the numerical simulation are considered. The weaknesses, strengths and prospects of the various methods are indicated, and results of different methods are compared and discussed.

Hoeijmakers, H. W. M.

"VORTEX WAKES IN AERODYNAMICS"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 1-1 to 1-12

A survey is presented of the physics of vortex wakes as occur in the flow about aircraft configurations. The emphasis is on fundamental aspects of the flows and on the assessment of the mathematical models that can be used for numerically simulating vortex wakes.

Hoeijmakers, H. W. M.

"MODELING AND NUMERICAL SIMULATION OF VORTEX FLOW IN AERODYNAMICS"

Proceedings of Fluid Dynamic Panel Symposium, Vortex Flow Aerodynamics, AGARD, CP-494, Scheveningen, The Netherlands, October 1990, pp. 1-1 to 1-46

A review is presented of mathematic models of different level of approximation for and their application to the numerical simulation of vortical type flows occurring in subsonic and transonic aircraft aerodynamics. The paper covers computational methods for predicting the downstream development of vortex wakes as well as methods for simulating the detailed characteristics of configurations with leading-edge or body vortices.

Hoeijmakers, H. W. M. and Vaatstra, W.

"HIGHER-ORDER PANEL METHOD APPLIED TO VORTEX SHEET ROLL-UP"

NLR-MP-81059-U, October 1982, National Aerospace Lab., Amsterdam, Netherlands

The paper describes a computational method for two-dimensional vortex sheet motion in incompressible flow. The procedure utilizes a second-order panel method, an adaptive panel scheme and a concept for treating highly rolled-up portions of the vortex sheet. Results are presented for the roll-up of the wake behind an elliptically loaded wing, a ring wing (nacelle), a fuselage/part-span-flap/wing combination and a delta wing with leading-edge vortex sheets. The examples demonstrate that the method is capable to describe complicated vortex sheet motion in a reliable and stable manner.

Hoeijmakers, H. W. M., Vaatstra, W. and Verhaagen, N. G.

"VORTEX FLOW OVER DELTA AND DOUBLE-DELTA WINGS"

J. Aircraft, Vol. 20, No. 9, September 1983, pp. 825-832

A theoretical and experimental investigation of the flow about a slender delta wing and two double-delta wings is described. The objective of the investigation is to develop accurate computational

methods for the vortex flow about slender wings and strake-wing configurations. Numerical results of computational methods developed for the flow about slender wings are compared with experimental results of the present and of earlier investigations. It is demonstrated that satisfactory numerical results are obtained for the normal force, pressure distribution, as well as vortex position and vortex sheet geometry. It is shown that for analyzing the structure of complex vortex flow the laser light-sheet flow visualization technique is very useful. Results of the flow visualization are presented for the flow about the delta wing and the double-delta wing. Based on the results for the double-delta wings, a new vortex sheet model is proposed for these wings involving a single-branched strake vortex and a double-branched wing vortex.

Hoekstra, T. J., Fang, R., Leijnse, C. and Renirie, L.

"CERTIFICATION OF HELICOPTERS FOR USE ON BOARD SHIP"

Europort Naval Conference, Amsterdam, November 1978

Although helicopter manufacturers usually define limits for the safe operation of a helicopter, this generally applies to a rigid platform situation only. For operation from ships, additional limitations must be observed. This paper states the requirements for the development of adapted operating procedures and the determination of new limitations to ensure optimum use and adequate safety for helicopters in this field. The relevant certification test procedure, as carried out by the National Aerospace Laboratory, is described.

Hoerner, S.

"AERODYNAMIC SHAPE OF THE WING TIPS"

Technical Report No. 5752, May 1969, USAF Wright-Patterson Air Force Base, Dayton, Ohio.

A study was made of the aerodynamic characteristics of wing tips, as well as experimental investigations concerning the mechanism of the tip vortices and the lift/drag ratio of a wing fitted with differently shaped wing tips. Results show there are two ways in which the wing tips affect flow and forces on a wing: considering the tip vortices the effective span of a wing does not coincide with the geometrical mean, i.e., the geometrical location of the tip vortices depends on the shape of the wing tips; and that some parasitic drag originates from the wing tips, its amount also depending upon the shape of the wing tip. Using these results, an optimum wing-tip shape is described. This wing tip has a sharp side edge, its plane form shows a corner at the trailing edge and its upper surface extends approximately straight to the end. Employing this kind of wing tip the climbing speed is increased in the order of 1 ft/sec and the range by 1 or 2 percent, in comparison to disadvantageous tip shapes.

Hofbauer, T.

"NUMERISCHE UNTERSUCHUNGEN ZUM EINFLUSS VON WINDSCHERUNG UND TURBULENZ AUF FLUGZEUGWIRBELSCHLEPPEN"

Dr.-Ing. Thesis, November 2002, University of Munich, Munich, Germany.

In several aspects, the behavior of aircraft wake vortices under situations of vertical wind shear is significantly different from non-shear scenarios and its operational real-time forecast is challenging. By means of numerical investigations of idealized scenarios, the influence of wind shear on the lateral and vertical transport of vortices is analyzed both, phenomenologically as well as in the scope of a sensitivity study. The results allow for the verification of controversial views and the benchmark of modeling approaches. Case studies of turbulent shear flows focus on the persistence of vortices. A detailed analysis of the flow fields evidence that unequal vortex decay rates can be attributed to the asymmetric distribution of secondary vorticity structures. The results moreover suggest that extended vortex lifespans can be expected under situations of wind shear. The unusual vortex behavior observed by means of a LIDAR measurement is reproduced by realistic simulations and permits to reveal potential causes. [In German.]

Hofbauer, T. and Gerz, T.

"EFFECTS OF NONLINEAR SHEAR ON THE DYNAMICS OF A COUNTER-ROTATING VORTEX PAIR"

Proceedings of 1st International Symposium on Turbulence and Shear Flow Phenomena, Santa Barbara, CA, 1999

Numerical simulations were conducted to investigate the influence of nonlinear vertical shear on the trajectories of a trailing vortex pair. Descending vortices which approach a shear layer begin to tilt and diverge. It is shown that the vortex whose vorticity is of opposite sign to the shear-layer vorticity can stall or even rebound, whereas the other vortex penetrates through the shear layer. The behavior of the vortices is highly sensitive to the vorticity distribution within the shear layer and cannot be described by circulation or maximum vorticity relations. When the vorticity distribution of the shear layer varies along the axis of the vortices, the interaction between shear and vortex is also modified in axial direction and presumably triggers a quickly growing instability of the vortex pair.

Hofbauer, T. and Gerz, T.

"SHEAR-LAYER EFFECTS ON THE DYNAMICS OF A COUNTER-ROTATING VORTEX PAIR"

AIAA Paper No. 2000-0758, Reno, NV, January 2000

The influence of three-dimensional wind-shear layers (jets) on the transport and decay of a counter-rotating vortex pair is investigated by means of direct numerical simulation. A laminar case is considered where the jet width varies periodically along the vortex axis. Further, the impact of two turbulence levels in the jet upon the vortex pair is studied. The initially laminar vortex pair penetrates from above into the jet and towards the ground. When penetrating the laminar jet, the wake vortices experience a sinusoidal perturbation but do not link. Contrarily, mutually independent dissolution of each vortex is observed when the jet is turbulent. The upstream vortex with vorticity opposing the vorticity of the upper shear layer of the jet starts to erode when it touches the upper flank of the turbulent jet, whereas the downstream vortex remains unaffected until it interacts with the lower

shear layer below the jet maximum. The vortex breakdown process and its spatial structure is discussed in detail.

Hofbauer, T. and Gerz, T.

"DECAY OF AIRCRAFT TRAILING VORTICES SUBJECTED TO TURBULENT CROSSWIND SHEAR"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

This study addresses the effect of turbulent wind shear on aircraft trailing vortex decay by means of direct numerical simulations (DNS). Prompted by the need for optimized separations, efforts are undertaken to develop an operational model, capable of forecasting the vortex behavior with respect to the variety of meteorological parameters. Thereby, the major shortcoming is the modeling of the crosswind shear effects, whose manifold impact on vortex migration and decay is most complex. Not only understanding the mechanisms of decay is an important element to predict vortex lifetimes, but to forecast the vortex trajectories as well. The objective of this study is to help clarify the underlying physical processes of vortex decay influenced by turbulent shear which in turn may contribute to the development of such a forecasting model.

Hofbauer, T. and Gerz, T.

"EFFECTS OF NONLINEAR SHEAR ON THE DYNAMICS OF A COUNTER-ROTATING VORTEX PAIR"

Proceedings of 1st International Symposium on Turbulence and Shear Flow Phenomena, Santa Barbara, CA, September 1999.

Numerical simulations were conducted to investigate the influence of nonlinear vertical shear on the trajectories of a trailing vortex pair. Descending vortices which approach a shear layer begin to tilt and diverge. It is shown that the vortex whose vorticity is of opposite sign to the shear-layer vorticity can stall or even rebound, whereas the other vortex penetrates through the shear layer. The behavior of the vortices is highly sensitive to the vorticity distribution within the shear layer and cannot be described by circulation or maximum vorticity relations. When the vorticity distribution of the shear layer varies along the axis of the vortices, the interaction between shear and vortex is also modified in axial direction and presumably triggers a quickly growing instability of the vortex pair.

Hofbauer, T. and Holzaepfel, F.

"BEHAVIOR OF AIRCRAFT WAKE VORTICES SUBJECTED TO WIND SHEAR"

AIAA Paper No. 2003-3813, Orlando, FL, June 2003

Among the meteorological parameters affecting the aircraft wake vortex behavior, wind shear effects constitute one of the most challenging tasks in modeling. Despite the significance for weather dependent reduced aircraft separations, the understanding of the interaction between vortices and ambient shear is far from complete. This article investigates issues of vortex transport and decay

influenced by laminar and turbulent shear events in terms of direct numerical simulations. The results show that ambient shear leads to vortex pair tilting, the rebound of vortices, and unbalanced vortex decay rates for the upwind and downwind vortex. The imbalance is a consequence of secondary vorticity structures, which stem from the stretching of ambient turbulent eddies. The numerical results are compared with current modeling approaches. It is argued that these approaches do not meet the requirements for an accurate prediction of vortex behavior. Further, the interaction between vortex pairs and shear layers is investigated by means of a parameter study which reveals the sensitivity of vortex transport on shear layer parameters. The analysis identifies behavior patterns and describes basic parametric relations and upper limits of vortex transport that may be used for parametrization.

Hoffman, E., Ivanescu, D., Shaw, C. and Zeghal, K.

"ANALYSIS OF CONSTANT TIME DELAY AIRBORNE SPACING BETWEEN AIRCRAFT OF MIXED TYPES IN VARYING WIND CONDITIONS"

Fifth EUROCONTROL/FAA ATM R&D Seminar, June 2003, Budapest, Hungary

This study analyzed the performance of constant time based airborne spacing under different operational conditions using fast time simulation. The effects of time-based spacing criteria, mixed aircraft types and wind conditions on the ability of an aircraft to maintain a time spacing behind a descending lead aircraft were investigated. The spacing performance of a previously used approximate time delay spacing criterion based on current lead aircraft speed was compared with an exact time delay spacing criterion based on lead aircraft position history. The exact time delay spacing criterion resulted in smaller time delay spacing errors and smoother true airspeed behavior. The exact time delay (60 s) criterion was then used to compare the spacing performance of a heavy aircraft following a light with a heavy aircraft following a heavy for different wind conditions. The results show that a heavy aircraft followed a light with approximately 40% more maximum time spacing error than a heavy aircraft followed a heavy. Different effects for constant and turbulent winds were observed. Maximum spacing error increased slightly with constant wind speed but always remained within 10 s up to maximum constant wind speeds of 87 knots (at 30 feet altitude) and 235 knots (at 29,000 feet altitude). Turbulent winds severely degraded stability particularly in cross wind conditions.

Hoffman, F. and van der Wall, B. G.

"THE VORTEX TRAJECTORY METHOD APPLIED TO HART II PIV DATA"

IB 111-2005/34, August 2005, DLR, Braunschweig, Germany

In October 2001 the HART II test campaign took place in the Large Low-speed Facility (LLF) of the German-Dutch Wind (DNW) tunnel. During the test, data of 1 TB were acquired including extensive wake data for the advancing and retreating side of the rotor plane. In the scope of this campaign, three test cases were distinguished: Baseline (BL), Minimum Noise (MN) and Minimum Vibration (MV). 3C-Particle Image Velocimetry (PIV) measurements were conducted to understand vortex roll up in the rotor wake as well as vortex aging to develop advanced simulation tools.

Hoffman, E. R. and Joubert, P. N.

"TURBULENT LINE VORTICES"

J. Fluid Mech., Vol. 16, Part 3, July 1963, pp. 395-411

An attempt has been made to establish the laws governing the flow in a turbulent line vortex. Up to the present time theoretical solutions for laminar flow have been used for comparison with experimental results for turbulent flow to find an 'eddy viscosity' term and its variation with various parameters. An approach is developed along lines like the methods used in turbulent boundary-layer theory and is found to be reasonably successful as far as the work has proceeded. It is predicted by theory, and confirmed by experiment, that the circulation in the vortex is proportional to the logarithm of radius under certain conditions. For the present experimental conditions, the vortices are found to be completely independent of viscosity effects when the parameter WZ/K exceeds 150, and above this value the experimental results may be correlated to give a universal distribution of circulation in the inner region of the vortex. Further experiments are necessary to verify and extend the results of these tests before any definite conclusions may be made regarding the circulation distribution in the outer core region of the vortex and the growth and development of the vortex.

Hoggard, Jr., H. P. and Hagerman, J. R.

"DOWNWASH AND WAKE BEHIND UNTAPERED WINGS OF VARIOUS ASPECT RATIOS AND ANGLES OF SWEEP"

NACA TN-1703, October 1948, Langley Aeronautical Lab., Langley Field, VA

An investigation has been made in the Langley 7- by 10-foot tunnel to determine the downwash angles and the dynamic-pressure ratios behind wings of various sweep angles and aspect ratios, and the aerodynamic force characteristics of the wings. A brief discussion of some of the effects of the more important variables is presented. The wake center line behind swept-forward wings was found to be located higher than the wake center line behind sweptback wings. A low tail position appears to be most stabilizing for all configurations investigated, with the exception of the short tail length behind the unswept wing at an angle of attack of 16 degrees. At low tail positions and low angles of attack the rate of change of downwash angle with angle of attack increases as sweepback decreases. At high tail positions and high angles of attack the reverse tends to be true.

Hoh, R. H.

"PILOT RATING SCALE FOR VORTEX HAZARD EVALUATION"

NASA CR-143836, June 1975, Systems Tech. Inc., Hawthorne, CA.

A pilot rating scale is developed for subjective assessment of hazard resulting from wake vortex encounter upsets. The development of the rating scale is based on a survey of 48 pilots regarding the

semantic properties of various phrases and a choice of formats for the rating scale. The rating scale can be used to define a hazard/non-hazard boundary as well as to determine a measure of the hazard.

Hohne, G., Fuhrmann, M. and Luckner, R.

"CRITICAL WAKE VORTEX ENCOUNTER SCENARIOS"

Aerospace Science and Technology, Vol. 8, 2004, pp. 689-701

A simulation-based method was developed to investigate the hazard of Wake Vortex Encounters (WVEs). This paper describes an important part of this method: the determination of worst-case WVE conditions, which is referred to as Worst-Case Search (WCS). The WCS results permit to reduce time and costs of WVE hazard related piloted simulator tests and allow the comparison of the hazard that vortices of different generator aircraft exert on a follower aircraft. The WCS is based on a high fidelity, offline simulation of the follower aircraft that includes the interacting wake vortex, a hazard criterion that rates the severity of each WVE, and a pilot model. It can be formulated as an optimization problem that is solved with the optimization tool MOPS (Multi Objective Parameter Synthesis). MOPS varied the encounter geometry until the simulation yields maximum values of the WVE hazard criterion. Worst-case encounter conditions for different parameters were investigated and sensitivity studies performed. The influence of the height above ground, the core radius, and the models for the wake vortex velocity profiles on the severity of a WVE was examined. To demonstrate the capability of the method, a comparison of the hazard of a WVE behind two different heavy transport aircraft for a 20t aircraft was made. The WCS method proved its applicability and delivered the worst-case encounter geometry.

Hohne, G., Fuhrmann, M. and Luckner, R.

"CRITICAL WAKE VORTEX ENCOUNTER SCENARIOS"

DLR Congress 2003, November 2003, Munchen, Germany.

A simulation-based method was developed to investigate the hazard of Wake Vortex Encounters (WVEs). This paper describes an important part of this method: the determination of worst-case WVE conditions, which is referred to as Worst-Case Search (WCS). The WCS results permit to reduce time and costs of WVE hazard related piloted simulator tests and allow the comparison of the hazard that vortices of different generator aircraft exert on a follower aircraft. The WCS is based on a high fidelity, offline simulation of the follower aircraft that includes the interacting wake vortex, a hazard criterion that rates the severity of each WVE, and a pilot model. It can be formulated as an optimization problem that is solved with the optimization tool MOPS (Multi Objective Parameter Synthesis). MOPS varied the encounter geometry until the simulation yields maximum values of the WVE hazard criterion. Worst-case encounter conditions for different parameters were investigated and sensitivity studies performed. The influence of the height above ground, the core radius, and the models for the wake vortex velocity profiles on the severity of a WVE was examined. To demonstrate the capability of the method, a

comparison of the hazard of a WVE behind two different heavy transport aircraft for a 20t aircraft was made. The WCS method proved its applicability and delivered the worst-case encounter geometry.

Hoiby, O. W. and Van der Blik, J. A.

"LATERAL BLOWING FROM THE TIP OF A LOW ASPECT RATIO WING"

Technical Note 25, February 1965, von Karman Institute for Fluid Dynamics, Rhode-Saint-Genese, Belgium.

The pressure distribution of an aspect ratio two rectangular wing with lateral blowing from the tip was measured. It was found that lateral blowing increases the lift at all lateral stations with an extra lift increase near the tip. The stall angle of attack was little affected by lateral blowing.

Holbrook, G. T.

"VORTEX WAKE HAZARD ANALYSIS INCLUDING THE EFFECT OF THE ENCOUNTERING WING ON THE VORTEX"

M.S. Thesis, August 1985, George Washington Univ., Washington, DC.

This thesis addresses the problem of vortex wakes and their impact on airport capacity. Dynamic vortex simulations were performed over a wide range of vortex generator and following aircraft pairs with, for the first time, an analysis of the effect of the encountering wing on the vortex and the resulting change in the roll response of the wing. The mutual interference between a wing and a vortex was accounted for by coupling the wing and vortex and applying the conservation of angular momentum flux in a control volume enclosing the wing. The following aircraft model incorporated a roll control authority based on minimum design requirements and roll responses to vortex encounters were predicted with and without roll control applied. The predictions were used to produce maps of acceptable vortex generator and following aircraft pairs. This allowed a generalized determination of the effects of the vortex generator span load, wake decay, and the mutual influence of the wing and vortex on predicted roll upsets.

Holbrook, G. T., Dunham, D. M. and Greene, G. C.

"VORTEX WAKE ALLEVIATION STUDIES WITH A VARIABLE TWIST WING"

NASA-TP-2442, November 1985, NASA Langley Research Center, Hampton, VA

Vortex wake alleviation studies were conducted in a wind tunnel and a water towing tank using a multisegmented wing model which provided controlled and measured variations in span load. Fourteen model configurations are tested at a Reynolds number of one million and a lift coefficient of 0.6 in the Langley 4- by 7-Meter Tunnel and the Hydronautics Ship Model Basin water tank at Hydronautics, Inc., Laurel, MD. Detailed measurements of span load and wake velocities at one semispan downstream correlate well with each other, with inviscid predictions of span load and wake

roll up, and with peak trailing-wing rolling moments measured in the far wake. Average trailing-wing rolling moments are found to be an unreliable indicator of vortex wake intensity because vortex meander does not scale between test facilities and free-air conditions. A tapered-span-load configuration, which exhibits little or no drag penalty, is shown to offer significant downstream wake alleviation to a small trailing wing. The greater downstream wake alleviation achieved with the addition of spoilers to a flapped-wing configuration is shown to result directly from the high incremental drag and turbulence associated with the spoilers and not from the span load alteration they cause.

Holforty, W. L.

"FLIGHT-DECK DISPLAY OF NEIGHBORING AIRCRAFT WAKE VORTICES"

PhD Thesis, June 2003, Stanford University, Stanford, CA.

Over the coming decades, aviation operations are predicted to rise steadily, increasing the burden on already congested and constrained airspace. A major factor governing the safe minimum separation distance between aircraft is the hazard generated by the wake of neighboring aircraft. Unaware of their proximity to other traffic, aircraft have encountered the wake turbulence of neighboring aircraft tens of miles ahead of them with serious or fatal consequences. The wake display described herein is a perspective view, synthetic vision, flight deck display that enables flight crews to 'see' neighboring aircraft, as well as their wakes via a predictive algorithm. Capable of enhancing the situational awareness with respect to the wake-vortex encounter hazard by enabling the flight crew to see the relative position of their aircraft with respect to the wake hazard, the display may allow for a decrease in the standard aircraft spacing to those now used in VFR conditions and an increase in airport and airspace capacity. At present, there is no mechanism in place in the National Airspace System that warns pilots of potential wake vortex encounters. The concept of a wake vortex display addresses the need for a real-time wake vortex avoidance scheme available directly to the pilot. The wake display has been evaluated under both simulated and actual flight conditions. Thirteen pilots with flight experience ranging from a student pilot to commercial airline and military pilots served as pilot test subjects evaluating the display under simulated conditions. The pilot test subjects completed a survey concerning their knowledge and understanding of wake vortices prior to the simulation data trials and, after the trials, they completed a pilot evaluation and post-flight survey rating their experience and providing feedback for the display design. One test pilot and four guest pilots flew the display during the in-flight evaluations incorporating three wake encounter scenarios. They reported a significant increase in their awareness of the position and movement of the wake and, using the display, they were easily able to maneuver the aircraft not only to avoid the wake, but also to find the wake for experimental verification. The simulations and flight tests demonstrated that synthetic vision based on theoretical predictions can enhance a pilot's situational awareness of the wake vortex encounter hazard.

Holforty, W. L. and Powell, J. D.

"FLIGHT DECK DISPLAY OF AIRBORNE TRAFFIC WAKE VORTICES"

20th DASC Conference, Paper No. 154, Session 2A, Daytona Beach, FL, October 2001

Over the coming decades, aviation operations are predicted to rise steadily, increasing the burden on already congested and constrained airports and terminal areas. It has long been recognized that a major factor governing the safe minimum separation distance between aircraft is the hazard associated with the wake generated by the preceding aircraft. A flight deck display that allows the pilot to 'see' the neighboring aircraft, as well as its wake, may allow for a decrease in spacing and an increase in airport and airspace capacity, while maintaining safe separation distances from wake vortices. This research evaluates a model based on aircraft parameters that are readily available in flight to predict aircraft wake vortices in real time. Using this model, several graphical representations of wake symbology were created for use in a 3-D perspective view flight deck display. This research determines the feasibility of this method of wake vortex display and ascertains the most favorable symbology for use in flight deck operations.

Holforthy, W. L. and Powell, J. D.

"DYNAMIC WAKE PREDICTION AND VISUALIZATION WITH UNCERTAINTY ANALYSIS"

US Patent 6,963,291 B2, November 2005

A dynamic wake avoidance system utilizes aircraft and atmospheric parameters readily available in flight to model and predict airborne wake vortices in real time. A novel combination of algorithms allows for a relatively simple yet robust wake model to be constructed based on information extracted from a broadcast. The system predicts the location and movement of the wake based on the nominal wake model and correspondingly performs an uncertainty analysis on the wake model to determine a wake hazard zone (no fly zone), which comprises a plurality of 'wake planes' each moving independently from another. The system selectively adjusts dimensions of each wake plane to minimize spatial and temporal uncertainty, thereby ensuring that the actual wake is within the wake hazard zone. The predicted wake hazard zone is communicated in real time directly to a user via a realistic visual representation. In an example, the wake hazard zone is visualized on a 3-D flight deck display to enable a pilot to visualize or 'see' a neighboring aircraft as well as its wake. The system substantially enhances the pilot's situational awareness and allows for a further safe decrease in spacing, which could alleviate airport and air-space congestion.

Hollingsworth, M. A. and Richards, E. J.

"ON THE SOUND GENERATED BY THE INTERACTION OF A VORTEX AND A SHOCK WAVE"

Aeronautical Research Council Report 18257, February 1956, University of Southampton, Southampton, UK.

Recent work by Ribner has been utilized to estimate the distribution of intensity in the sound wave resulting from the interaction between a vortex and a shock wave, to obtain the order of magnitude of

the sound pressure obtained and the dependence of their magnitude upon shock strength and vortex strength. The distribution is compared with a Schlieren photograph of the interaction. Based on the analysis, the sound pressures are found to increase steadily with both Mach number and vortex strength. Particular estimates of sound levels depend critically upon the flow condition, but curves are attached for a typical wind-tunnel case indicating very intense sound levels for small percentage velocity fluctuations.

Hollingsworth, M. A. and Richards, E. J.

"A SCHLIEREN STUDY OF THE INTERACTION BETWEEN A VORTEX AND A SHOCK WAVE IN A SHOCK TUBE"

Aeronautical Research Council Report 17985, November 1955, University of Southampton, Southampton, UK.

A method utilizing the reflected compression shock in a shock tube has been successfully developed to obtain Schlieren photographs of the sound wave pattern resulting from the interaction between a vortex and a shock wave. The interaction results in the propagation into the air behind the shock wave of a sound wave of directionally varying intensity and sign. The amplitude of this sound wave appears to depend very directly upon the vortex strength: its dependence upon the shock strength is still under investigation.

Holloway, A. G. L. and Richardson, S.

"DEVELOPMENT OF A TRAILING VORTEX FORMED WITH SPANWISE TIP JETS"

Journal of Aircraft, Vol. 44, No. 3, May-June 2007, pp. 845-857

Trailing vortices from a NACA0015 ($AR = 5$) wing were formed with spanwise tip jets to allow the study of vortex core distortions on the development of vortex size and speed. The wing-tip jets were formed from small holes arranged along the periphery of the wing cross section. Experiments covered a wide range of tip jet blowing rates for a fixed-wing incidence of 5 deg and chord Reynolds number of 100,000. Measurements of mean velocity, mean vorticity, and turbulence kinetic energy in the wake were made up to 32 chords downwind using hot-wire anemometry. The tip vortex was observed to envelop the jet and subsequently grow in diameter at a substantially higher rate than the vortex formed without tip jets. The circumferential speed of the vortex formed with tip jets was higher in the near field, but declined sharply with downstream distance. At 32 chords downwind, the vortex formed with tip jets evolved into an axisymmetric form similar to a natural vortex, but with a diameter up to three times larger and a peak circumferential velocity three times less. The turbulence intensity measured on the vortex core was 30% in the near wake and 10% at 32 chords downwind.

Holmes, J. F., Kerr, J. R., Lee, M. H. and Fossey, M. E.

"EXPERIMENTAL PULSED LASER REMOTE CROSSWIND MEASUREMENT SYSTEM - FEASIBILITY STUDY AND DESIGN"

FA-TR-76065, November 1976, Oregon Graduate Center, Beaverton, Oregon.

Recent activity regarding development of a pulsed laser, remote crosswind measurement system is described. This includes a more complete theoretical formulation which includes the log-amplitude perturbation. In addition, cw experimental work used to verify the theoretical formulation and the design and construction of a new pulsed crosswind system are described. The system uses a double pulsed 1.06-micron Nd:Yag laser, a sixteen-element arrayed receiver and space-time statistical averaging.

Holt, J. C. and Garry, K. P.

"DYNAMIC WIND TUNNEL SIMULATION OF AIRCRAFT WAKE VORTEX TRAJECTORY IN GROUND PROXIMITY"

AIAA Paper 2016-1069, January 2016, San Diego, CA.

The trajectory of the wake vortex generated by a transport aircraft wing during take-off and landing can influence the dispersion of the engine exhaust plume and therefore impact on local air quality in the vicinity of airports. A sub-scale atmospheric boundary layer wind tunnel (ABLWT) simulation, used to predict exhaust dispersion, would therefore need to include the effect of the wing wake. A preliminary series of wind tunnel measurements are presented which examine the effectiveness of both a quasi-static and moving-model simulation of a trailing vortex pair at nominally 1/200th scale, within an ABLWT. A simple flat plate delta planform wing, at incidence, is shown to be an effective vortex wake generator at this scale and Reynolds number (nominally 300,000). The trajectory of the vortices within the wake in the range $2 < (z/b) < 26$ are shown to be consistent with that reported for aircraft flight test; ground proximity is seen to influence both the lateral and vertical displacement of the vortex cores. Using this limited dataset, differences in vortex trajectory between a quasi-static and dynamic simulation only appear significant when an aircraft climb (+6 degrees to the horizontal) or descent (-3 degrees) profile is simulated.

Holzaepfel, F.

"AIRCRAFT WAKE VORTICES -- FROM FUNDAMENTAL RESEARCH TO OPERATIONAL APPLICATION"

Promet, Vol. 39, No. 1/2, 2014, pp. 14-22.

Aircraft trailing vortices constitute both a kaleidoscope of instructive fluid dynamics phenomena and a challenge for the sustained development of the safety and capacity of the air transportation system. An overview of the wake vortex issue is given commencing at its historical roots, proceeding with a sketch of the nature and characteristics of wake vortices resulting from field measurement and numerical simulation, and concluding with a depiction of the design and performance of wake vortex

simulation systems established for the prediction of dynamic aircraft separations in different flight phases and for sensitivity and risk analysis. [In German.]

Holzaepfel, F.

"ADJUSTMENT OF SUBGRID-SCALE PARAMETERIZATIONS TO STRONG STREAMLINE CURVATURE"

AIAA Journal, Vol. 42, No. 7, July 2004, pp. 1369-1602

A sub-grid scale model correction for large eddy simulations that address flow fields with embedded areas of poorly resolved strong streamline curvature effects is proposed. The devised modification is termed NaCoo and provides an isotropic correction of the sub-grid scale viscosity based on local centrifugal stability. The degree of stability is identified via a rotational Richardson number that is determined based on non-Galilean-invariant streamline curvature at every grid point. NaCoo allows for a more realistic representation of inadequately resolved coherent turbulent vortices. Its main benefits are: 1) conservation of the peak vorticity in the vortex cores, 2) reduction of vortex core radius growth rates, 3) an approach to properties of tangential velocity profiles found in experiments, 4) allowance for appropriate turbulence levels in the vicinity of the vortices, and 5) non suppression of vortex core meandering. The derivation of NaCoo, its properties, and sensitivity to numerical and vortex parameters are described in detail. Applications of the correction to single vortices and aircraft wake vortices in a quiescent and turbulent environment demonstrate the capabilities of the pragmatic correction.

Holzaepfel, F.

"PROBABILISTIC TWO-PHASE AIRCRAFT WAKE-VORTEX MODEL: FURTHER DEVELOPMENT AND ASSESSMENT"

Journal of Aircraft, Vol. 43, No. 3, May-June 2006, pp. 700-708

Further developments, applications, and assessments of the probabilistic two-phase aircraft wake-vortex model P2P are described. The wake-vortex model is applied to data of two field measurement campaigns accomplished at Tarbes airport, France. Measurements corroborate unambiguously the two-phase circulation decay anticipated by theory and parameterized by P2P. Vortex age and descent speed are adjusted to match effects of axial wind and glide-slope angle. Envelopes of vortex trajectories are expanded to consider tilting, stalling, and rebounding wake vortices caused by axial- and crosswind shear. For probabilistic model output a choice between arbitrary degrees of probability is established, and a stochastic prediction mode is introduced. In a deterministic scoring procedure, model performance is compared to the skill of another model. Probabilistic model performance is evaluated by the compilation of probability density distributions that relate wake vortex measurement data to the predicted envelopes.

Holzaepfel, F.

"PROBABILISTIC TWO-PHASE WAKE VORTEX DECAY AND TRANSPORT MODEL"

J. Aircraft, Vol. 40, No. 2, March-April 2003, pp. 323-331

A new parametric wake vortex transport and decay model is proposed that predicts probabilistic wake vortex behavior as a function of aircraft and environmental parameters in real time. The probabilistic two-phase wake vortex decay model (P2P) accounts for the effects of wind, turbulence, stable stratification, and ground proximity. The model equations are derived from the analytical solution of the spatiotemporal circulation evolution of the decaying potential vortex and are adapted to wake vortex behavior as observed in large-eddy simulations. Vortex decay progresses in two phases, a diffusion phase followed by rapid decay. Vortex descent is a nonlinear function of vortex strength. Probabilistic components account for deviations from deterministic vortex behavior inherently caused by the stochastic nature of turbulence, vortex instabilities, and deformations, as well as uncertainties and fluctuations that arise from environmental and aircraft parameters. The output of P2P consists of confidence intervals for vortex position and strength. To assign a defined degree of probability to the predictions reliably, the model design allows for the continuous adjustment of decay parameters and uncertainty allowances, based on a growing amount of data. The application of a deterministic version of P2P to the Memphis wake vortex database yields favorable agreement with measurements.

Holzaepfel, F.

"ANALYSIS OF POTENTIAL WAKE VORTEX ENCOUNTERS AT A MAJOR EUROPEAN AIRPORT"

Aircraft Engineering and Aerospace Technology, Vol. 89, Issue 5, 2017, pp. 634-643.

In this study, 12 potential wake vortex encounters that were reported at a major European airport have been investigated. Because almost all encounters occurred in ground proximity, most pilots conducted a go-around. The primary purpose of this study is to discriminate between incidents caused by wake vortex or rather by effects like wind shear or turbulence. Detailed knowledge of real-world encounter scenarios and identification of worst-case conditions during the final approach constitute highly relevant background information to assess the standard scenario used for the definition of revised wake turbulence separations.

Holzaepfel, F.

"PROBABILISTIC TWO-PHASE WAKE VORTEX DECAY AND TRANSPORT MODEL"

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diffusion phase followed by rapid decay. Vortex descent is a nonlinear function of vortex strength. Probabilistic components account for deviations from deterministic vortex behavior inherently caused by the stochastic nature of turbulence, vortex instabilities, and deformations, as well as uncertainties and fluctuations that arise from environmental and aircraft parameters. The output of P2P consists of confidence intervals for vortex position and strength. To assign a defined degree of probability to the predictions reliably, the model design allows for the continuous adjustment of decay parameters and uncertainty allowances, based on a growing amount of data. The application of a deterministic version of P2P to the Memphis wake vortex database yields favorable agreement with measurements.

Holzaepfel, F.

"EFFECTS OF ENVIRONMENTAL AND AIRCRAFT PARAMETERS ON WAKE VORTEX BEHAVIOR"

Journal of Aircraft, Vol. 51, No. 5, September-October 2014, pp. 1490-1500.

This study investigates the impact of meteorological parameters (crosswind, headwind, wind shear, thermal stratification, turbulent kinetic energy, dissipation rate, and density) and aircraft parameters (position, heading, speed, weight, span, and spanwise load factor) on wake-vortex behavior. Typical measurement uncertainties of these parameters, on one hand, and the range in which they typically reside, on the other hand, are mapped on variations of lateral and vertical position and lifetime of the wake vortices. For this mapping process the deterministic two-phase wake-vortex model is employed, complemented by some simple considerations, dimensional analysis, and sources from literature. Three scenarios comprising cruise conditions, flight within the atmospheric boundary layer, and ground proximity are considered. From these investigations the following ranking of the impact parameters has been deduced: wind, thermal stratification, turbulence, position, mass, and spanwise load factor. The relevance of the remaining parameters appears small.

Holzaepfel, F.

"SENSITIVITY ANALYSIS OF THE EFFECTS OF AIRCRAFT AND ENVIRONMENTAL PARAMETERS ON AIRCRAFT WAKE VORTEX TRAJECTORIES AND LIFETIMES"

AIAA Paper 2013-0363, January 2013, Grapevine, TX.

This study investigates the impact of aircraft parameters (position, heading, speed, weight, span, and spanwise load factor) and meteorological parameters (crosswind, headwind, wind shear, thermal stratification, turbulent kinetic energy, dissipation rate, and density) on wake vortex behavior. Typical measurement uncertainties of these parameters, on one hand, and the range in which they typically reside, on the other hand, are mapped on variations of lateral and vertical position and lifetime of the wake vortices. For this mapping process the D2P wake vortex model is employed complemented by some simple considerations, dimensional analysis, and sources from literature. Three scenarios comprising cruise conditions, flight within the atmospheric boundary layer, and ground proximity are considered. From these investigations the following ranking of the impact parameters has been

deduced: wind, thermal stratification, turbulence, position, mass, spanwise load factor. The relevance of the remaining parameters appears small.

Holzaepfel, F.

"PROBABILISTIC WAKE VORTEX DECAY MODEL PREDICTIONS COMPARED WITH OBSERVATIONS OF FOUR FIELD MEASUREMENT CAMPAIGNS"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

Predictions of the parametric aircraft wake vortex transport and decay model P2P are compared with field observations. The two-phase decay model predicts probabilistic wake vortex behavior as a function of aircraft and environmental parameters in real time. Observation data from field deployments accomplished at the International Airports Memphis and Dallas Fort Worth, from the WakeOP campaign performed at the airfield in Oberpfaffenhofen, Germany, and from the WakeToul campaign at Tarbes airport, France, are employed. Based on 211 Memphis cases, it is shown that the probabilistic model predicts conservative confidence intervals for vortex decay except for four cases in which constant background wind shear increases vortex lifetime. Nonetheless, the aircraft spacing reduction potential based on vortex decay appears small. In contrast, consideration of advection outside the lateral limits of a safety corridor results in a large potential spacing reduction. Vortex drift is investigated based on input from different wind measurement devices with a focus on the spatial and temporal variability of the crosswind. Safety corridor clearances based on short term weather forecasts yield promising results.

Holzaepfel, F.

"SURFACE STRUCTURE ON A GROUND SURFACE FOR ACCELERATING DECAY OF WAKE TURBULENCE IN THE SHORT FINAL OF AN APPROACH TO A RUNWAY"

US Patent Application, 2013/0313363 A1, November 2013.

The invention relates to a surface structure on a ground surface, located in the short final of an approach to a runway, with an associated start of the runway and a runway longitudinal axis. To attain accelerated decay of wake turbulence produced by an approaching aircraft, the surface structure has according to the invention a multiplicity of separate elevations with an elevation height ranging from 0.25-10 m, in particular from 1-5 m, wherein the individual elevations have a spacing between them, ranging from 1-600 m, 1-400 m, 1-200 m, 1-100 m, 1-50 m, 1-15 m, 1-10 m, or in particular 2-8 m.

Holzaepfel, F. and de Bruin, A.

"AIRCRAFT WAKE-VORTEX EVOLUTION IN GROUND PROXIMITY: ANALYSIS OF FIELD MEASUREMENT DATA AND PARAMETERIZATION"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

Field measurement data of 237 wake vortex pairs and respective environmental conditions acquired at Frankfurt Airport by means of lidar, Sodar/RASS, and ultrasonic anemometer are used to analyze wake vortex behavior in ground proximity. Statistics of descent, rebound, and lateral transport characteristics are established. Effects of crosswind, headwind, atmospheric turbulence and stable temperature stratification are evaluated. Already light crosswind turns out to be sufficient to cause pronounced asymmetric rebound characteristics. Exceptional cases with strong rebounds caused by detached shear layers and obstacles are introduced and estimates of the time needed to clear the runway from wake vortices by advection are provided. The impact of turbulence, wind and stratification on wake vortex decay turns out to be weak and difficult to verify. Nevertheless, a clear correlation of turbulence and crosswind on wake vortex decay can be established by fitting the equation for circulation evolution of the P2P wake vortex model to the measurement data. Based on the analyses of field measurement data and numerical simulation results vortex decay and rebound characteristics are parameterized and implemented into the probabilistic two-phase aircraft wake-vortex model (P2P). The devised parameterizations are also adapted to the conditions prevailing at vortex generation heights below one vortex spacing. Comparison to wake predictions out of ground effect indicates that in ground effect (i) the rapid-decay phase progresses slower, (ii) wake vortex evolution can be predicted with improved accuracy, and (iii) fair prediction skill requires only limited environmental data.

Holzaepfel, F. and Gerz, T.

"AIRCRAFT WAKE VORTICES: FROM FUNDAMENTAL RESEARCH TO OPERATIONAL APPLICATION"

In: Atmospheric Physics, Research Topics in Aerospace, U. Schumann (editor), Springer-Verlag Berlin Heidelberg, 2012 pp. 219-237.

Aircraft trailing vortices constitute both a kaleidoscope of instructive fluid dynamics phenomena and a challenge for the sustained development of the safety and capacity of the air-transportation system. This section gives an overview of the wake vortex issue commencing at its historical roots, proceeding with a sketch of the nature and characteristics of wake vortices resulting from field measurements and numerical simulation, and concluding with a depiction of the design and performance of wake vortex simulation systems established for the prediction of dynamic aircraft separations in different flight phases and for sensitivity and risk analysis.

Holzaepfel, F. and Gerz, T.

"TURBULENT DECAY MECHANISMS OF WAKE VORTICES IN THE STABLY STRATIFIED ATMOSPHERE"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

The decay of wake vortices in the stably stratified atmosphere is investigated by means of large eddy simulations. Results of in-situ measurements in the wakes of different aircraft are used to find

appropriate initializations for the simulation of wake turbulence in the quiescent atmosphere. Furthermore, cases with weak atmospheric turbulence are investigated. It is shown that the early development of the vortices is not affected by turbulence and develops almost identically as in 2D simulations. In quiescent atmosphere the subsequent decay is controlled by short-wave disturbances which strongly interfere with stable stratification effects whereas in the cases with atmospheric turbulence the long-wave instability is dominantly promoted. For very strong stratification it is observed that wake vortices may rebound but lose most of their strength before reaching the flight level. Finally, the simulation results are compared to the predictive capabilities of Greene's approximate model.

Holzaepfel, F. and Gerz, T.

"TWO-DIMENSIONAL WAKE VORTEX SIMULATIONS IN THE STABLY STRATIFIED ATMOSPHERE."

AIAA Paper No. 1998-2857, Albuquerque, NM, June 1999.

The effects of stable stratification on aircraft wake vortices are investigated by means of high-resolution two-dimensional simulations. The simulations elucidate that the vortices first decelerate and then accelerate their descent, where they largely conserve their circulation. This complex behavior is explained by the kinematic interaction of the wingtip vortices and the secondary vorticity generated by baroclinity. It is found that the impulse of the whole system, including primary and secondary vorticity, is oscillating with the Brunt-Vaisala frequency which implies that the wingtip vortices themselves do not. Nevertheless, the buoyancy force that acts on the oval enveloping the wingtip vortices develops, at least for the first quarter of the Brunt-Vaisala period, exactly as it is expected for an ideal and vertically displaced particle. This results in a relation between the descent height and the size of the oval.

Holzaepfel, F. and Gerz, T.

"PERFORMANCE OF THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS AT FRANKFURT AIRPORT"

ICAS 2008, Anchorage, AK, Sept. 2008.

The design and performance of the Wake Vortex Prediction and Monitoring System WSVBS are described. The WSVBS has been developed to tactically increase airport capacity for approach and landing on closely-spaced parallel runways. It is thought to dynamically adjust aircraft separations dependent on weather conditions and the resulting wake vortex behavior without compromising safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behavior and respective safety areas. As a safety net a LIDAR monitors the correctness of WSVBS predictions in the most critical gates at low altitude. The WSVBS is integrated in the arrival manager AMAN of DLR. Within 66 days of performance test at Frankfurt airport it was found that the system ran stable and the predicted minimum separation times were safe. The capacity improving concepts of operation could have been used in 75 percent of

the time. From fast-time simulations the eventual capacity gain for Frankfurt was estimated to be 3 percent taking into account the real traffic mix and operational constraints in the period of one month.

Holzaepfel, F. and Gerz, T.

"TWO-DIMENSIONAL WAKE VORTEX PHYSICS IN THE STABLY STRATIFIED ATMOSPHERE"

Aerospace Science and Tech., Vol. 3, No. 5, May 1999, pp. 261-270

The effects of stable stratification on aircraft wake vortices are investigated by means of high-resolution two-dimensional simulations. The simulations elucidate that the vortices first decelerate and then accelerate their descent, where they largely conserve their circulation. However, for very stable stratification the tip vortices may rise again to the flight path. The underlying physical mechanisms are revealed by means of a point vortex method and are examined complementarily by balancing the impulse of the wake vortices. It is shown that the prominent effects, deceleration, detrainment, and acceleration are caused by the kinematic interaction of the vorticity generated by baroclinity and the primary vorticity. Furthermore, it is found that the impulse of the 'whole' system, including the detrained secondary vorticity, is oscillating with the Brunt-Vaisala frequency which implies that the wingtip vortices themselves do not. Finally, a local shear-number is proposed which takes into account the interaction of primary and secondary vorticity and can describe the instantaneous tendency of wake vortices to accelerate or to decelerate.

Holzaepfel, F. and Gerz, T.

"AIRCRAFT WAKE VORTEX CHARACTERISTICS IN THE STABLY STRATIFIED ATMOSPHERE"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

Aircraft wake vortices (WVs) may exert a danger on a following aircraft if the separation between the leading and following aircraft is not sufficient. In view of the expected growth of air traffic, increasing demands on the capacity and safety of international airports have to be faced. A promising approach to increase the capacity of airports is to model the temporal evolution of WVs to forecast their lifespan. It is meanwhile generally accepted that meteorological conditions such as turbulence, stratification and shear dominantly determine the development of WVs. We focus on the impact of the stably stratified atmosphere, an issue which has been discussed controversially for years. Based on 2-D and large eddy simulations as well as simple vortex element methods the behavior of WVs is analyzed. Depending on the degree of stratification we observe both an accelerated and a decelerated descent of WVs. Both effects are explained by the interaction of the WV's flow field with vorticity produced due to baroclinicity.

Holzaepfel, F. and Kladetzke, J.

"ASSESSMENT OF WAKE-VORTEX ENCOUNTER PROBABILITIES FOR CROSSWIND DEPARTURE SCENARIOS"

Journal of Aircraft, Vol. 48, No. 3, May-June 2011, pp. 812-822.

The WakeScene-D (Wake Vortex Scenarios Package for Departure) software package has been developed for comprehensive airspace simulations of takeoff and departure. WakeScene-D consists of modules that model traffic mix, aircraft trajectories, meteorological conditions, wake-vortex evolution, and potential hazard area. The software package estimates the probability to encounter wake vortices in different traffic and crosswind scenarios using Monte Carlo simulation in a domain ranging from the runway to an altitude of 3000 ft above ground. A comparison with measured vortex tracks of about 10,000 departures from runway 25R of Frankfurt airport indicates good agreement of global wake-vortex transport characteristics in ground proximity. The standard departure situation employing a 2 min aircraft separation is compared with scenarios with reduced departure separations and various crosswind conditions. Comprehensive sensitivity analyses have been conducted that are briefly recapitulated. Effects related to departure-route combinations and wind-direction sectors are reported in more detail. Finally, an advanced scenario with an asymmetric crosswind criterion is introduced.

Holzaepfel, F. and Kladetzke, J.

"WAKE VORTEX ENCOUNTERS DURING TAKE-OFF AND DEPARTURE: SENSITIVITY ANALYSIS AND WORST CASE SEARCH"

CREDOS Report D3-9, November 2009, DLR, Oberpfaffenhofen, Germany.

This report describes Monte Carlo simulations of the airspace during take-off and departure with respect to wake vortex encounter probabilities under different traffic and crosswind situations with the software package WakeScene-D. The investigated scenarios can be split into (i) sensitivity analyses and (ii) validation cases that shall deepen the understanding of WakeScene-D and the confidence into the software package and into (iii) scenarios serving as a reference representing the current situation and (iv) the target scenarios for crosswind reduced separations and the related safety case. The current investigations allow for suggestions how CREDOS operations could be realized without increasing the risks compared to the reference scenario.

Holzaepfel, F. and Kladetzke, J.

"ASSESSMENT OF WAKE VORTEX ENCOUNTER PROBABILITIES FOR CROSSWIND DEPARTURE SCENARIOS"

CEAS 2009 European Air and Space Conference, October 2009, Manchester, UK.

This paper briefly describes the operating sequence of WakeScene-D (Wake Vortex Scenarios Simulation Package for Departure) and the employed sub-models. Next, a reference scenario is introduced which shall represent the real current departure situation. Then the statistics achieved with reduced aircraft departure separations and different crosswind thresholds are discussed. Finally, the paper highlights a selection of the most interesting results found in the conducted comprehensive sensitivity analyses. The investigated parameters of these sensitivity analyses comprise sample size, aircraft type combination, take-off weight, departure route combination, flight path adherence, wind

direction, wake vortex model, and a comparison to the arrival situation. On one hand, these sensitivity analyses help to increase the confidence in the software package and, on the other hand, they allow identifying the parameters that control encounter probabilities during takeoff and departure. In a next step the knowledge of these key parameters may enable the optimization of criteria for reduced aircraft separation.

Holzaepfel, F. and Robins, R. E.

"PROBABILISTIC WAKE VORTEX DECAY MODEL PREDICTIONS COMPARED WITH OBSERVATIONS"

AIAA Paper No. 2003-3809, June 2003, Orlando, FL.

Predictions of the parametric aircraft wake vortex transport and decay model P2P are compared with field observations. The two-phase decay model predicts probabilistic wake vortex behavior as a function of aircraft and environmental parameters in real time. Observation data from field deployments accomplished at the International Airports Memphis and Dallas Fort Worth, and from the WakeOP campaign performed at the airfield in Oberpfaffenhofen, Germany are employed. In a scoring procedure, the predictive capabilities of a deterministic version of P2P are compared to Sarpkaya's model. Based on 211 Memphis cases, it is shown that the probabilistic model predicts conservative confidence intervals for vortex decay except for four cases in which constant background wind shear increases vortex lifetime. Nonetheless, the aircraft spacing reduction potential based on vortex decay appears small. In contrast, consideration of advection outside the lateral limits of a safety corridor results in a large potential spacing reduction. Vortex drift is investigated based on input from different wind measurement devices with a focus on the spatial and temporal variability of the crosswind. Safety corridor clearances based on short term weather forecasts yield promising results. Further, it is found that shear layers may modify vortex transport such that predicted uncertainty allowances are exceeded.

Holzaepfel, F. and Robins, R. E.

"PROBABILISTIC TWO-PHASE AIRCRAFT WAKE- VORTEX MODEL: APPLICATION AND ASSESSMENT"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1117-1126

Predictions of the parametric probabilistic two-phase aircraft wake-vortex transport and decay model P2P are compared with field observations. The two-phase decay model predicts probabilistic wake vortex behavior as a function of aircraft and environmental parameters in real time. Observation data from field deployments accomplished at the International Airports Memphis and Dallas Fort Worth, and from the WakeOP campaign performed at the airfield in Oberpfaffenhofen, Germany are employed. In a scoring procedure, the predictive capabilities of a deterministic version of P2P are compared to Sarpkaya's model. Based on 211 Memphis cases, it is shown that the probabilistic model predicts conservative confidence intervals for vortex decay except for four cases in which constant background wind shear increases vortex lifetime. Nonetheless, the aircraft spacing reduction potential based on vortex decay appears small. In contrast, consideration of advection outside the lateral limits

of a safety corridor results in a large potential spacing reduction. Vortex drift is investigated based on input from different wind measurement devices with a focus on the spatial and temporal variability of the crosswind. Safety corridor clearances based on short term weather forecasts yield promising results. Further, it is found that shear layers may modify vortex transport such that predicted uncertainty allowances are exceeded.

Holzaepfel, F. and Robins, R. E.

"PROBABILISTIC WAKE VORTEX DECAY MODEL PREDICTIONS COMPARED WITH OBSERVATIONS"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002.

A parametric model capable of reliably predicting vortex positions and strengths in real-time in a measured or forecasted atmospheric environment along the glide slope might permit air-traffic controllers to ease some of the regulations without loss of safety. All existing parametric wake vortex models predict deterministic vortex behavior. Not specified are deviations from predicted values inherently caused by the stochastic nature of turbulence, complex vortex instabilities and deformations, and the uncertainty of environmental parameters that determine the vortices' behavior in the atmospheric boundary layer. The probabilistic two-phase wake vortex decay model (P2P) is designed to predict wake vortex behavior within defined confidence intervals. For this purpose, the model concept allows for the continuous adjustment of decay parameters and uncertainty allowances, based on a growing amount of data. The model accounts for the effects of wind, turbulence, stable thermal stratification, and ground proximity.

Holzaepfel, F. and Steen, M.

"Aircraft Wake-Vortex Evolution in Ground Proximity: Analysis and Parameterization"

AIAA Paper 2006-1077, January 2006, Reno, NV.

Holzaepfel, F. and Steen, M.

"AIRCRAFT WAKE-VORTEX EVOLUTION IN GROUND PROXIMITY: ANALYSIS AND PARAMETERIZATION"

AIAA Journal, Vol. 45, No. 1, January 2007, pp. 218-227

Field measurement data of 288 wake-vortex pairs and respective environmental conditions acquired at Frankfurt Airport by means of light detection and ranging, sound detection and ranging/radio acoustic sounding system, and ultrasonic anemometer are used to analyze wake vortex behavior in ground proximity. Exceptional cases with strong rebounds caused by detached shear layers and obstacles are introduced and estimates of the time needed to clear the runway from wake vortices by advection are provided. The impact of turbulence and crosswind on wake vortex decay proves to be weak, whereas already light crosswind turns out to be sufficient to cause pronounced asymmetric

rebound characteristics. Based on the analyses vortex decay and rebound characteristics are parameterized and implemented into the probabilistic two-phase aircraft wake vortex model. Deterministic and probabilistic prediction skill of the enhanced vortex model are assessed. Comparison to wake predictions out of ground effect indicates that in ground effect 1) the rapid-decay phase progresses slower, 2) wake vortex evolution can be predicted with improved accuracy, and 3) fair prediction skill requires only limited environmental data.

Holzaepfel, F. and Tranapp, N.

"FUSION OF SINGLE-POINT AND DISTRIBUTED AERODYNAMIC DATASETS FOR WAKE ENCOUNTER FLIGHT SIMULATION"

AIAA Paper 2007-6312, August 2007, Hilton Head, SC.

This paper presents an approach for the fusion of high-fidelity single point aerodynamic datasets with simplified aerodynamic datasets containing pressure distribution information to allow real-time simulation of flight under atmospheric conditions with high local wind gradients, where the aerodynamic forces and moments acting on the aircraft may no longer be computed based on the wind speed at one point of the aircraft. The approach presents a solution that saves the constraint that, for uniform atmospheric disturbances covering the whole aircraft, the distributed aerodynamic model delivers the same forces and moments as the single point data set. This approach is useful for many practical purposes, as very often extensive high fidelity single point aerodynamic data is available from a fusion of flight tests, wind tunnel measurements and computations whereas in many cases the pressure distribution leading to those forces and moments is not available from the same source or at the same level of fidelity. The algorithm is based on influence coefficients describing the contribution of strips or panels of the aircraft to the total aerodynamic force and moments. To ensure consistence with the single point data set, force and moment constraints for homogeneous, uniform disturbances are formulated and a possible solution for their enforcement is presented. Cross-flow effects due to the inhomogeneous flow conditions in disturbed air however are neglected.

Holzaepfel, F., Dengler, K., Gerz, T. and Schwarz, C.

"PREDICTION OF DYNAMIC PAIRWISE VORTEX SEPARATIONS FOR APPROACH AND LANDING"

AIAA Paper No. 2011-3037, June 2011, Honolulu, Hawaii.

Design and performance of the Wake Vortex Prediction and Monitoring System WSVBS are described. The WSVBS has been developed to tactically increase airport capacity for approach and landing on single runways as well as closely-spaced parallel runways. It is thought to dynamically adjust aircraft separations dependent on weather conditions and the resulting wake vortex behavior without compromising safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behavior and respective safety areas. LIDAR monitors the correctness of WSVBS predictions in the most critical gates at low altitude. The WSVBS is integrated in the arrival manager AMAN of DLR. Performance tests of the WSVBS have

been accomplished at Frankfurt airport in winter 1006/07 and at Munich Airport in summer 2010. Aircraft separations for landings on single runways have been compared employing the concepts of either heavy-medium weight class combinations or dynamic pairwise separations where individual aircraft type pairings are considered. For the very conservative baseline setup of the WSVBS the potential capacity gains of dynamic pairwise operations for single runways appear to be very small. On the other hand, the consideration of individual aircraft types and their respective wake characteristics may almost double the fraction of time when radar separation could be applied.

Holzaepfel, F., Frech, M., Gerz, T., Tafferner, A., Hahn, K.-U., Schwarz, C., Joos, H.-D., Korn, B., Lenz, H., Luckner, R. and Hohne, G.

"AIRCRAFT WAKE VORTEX SCENARIOS SIMULATION PACKAGE -- WAKESCENE"

ICAS 2008, September 2008, Hamburg, Germany.

Wake-vortex advisory systems and modifications of ATC procedures that aim at increasing airport capacity without compromising safety have been developed in recent years. Prior to the introduction of such systems the associated risks must be assessed. The WakeScene (Wake Vortex Scenarios Simulation) Package allows to assess the encounter probability behind different wake-vortex generating aircraft during approach and landing. WakeScene consists of modules that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard area. This manuscript introduces the operating sequence of WakeScene, the employed sub-models and data bases, the simulation environment and evaluation tools together with the so far accomplished validation work. Examples of WakeScene applications and an outlook on further developments of the software package conclude the report.

Holzaepfel, F., Frech, M., Gerz, T., Tafferner, A., Hahn, K.-U., Schwarz, C., Joos, H.-D., Korn, B., Lenz, H., Luckner, R. and Hohne, G.

"AIRCRAFT WAKE VORTEX SCENARIOS SIMULATION PACKAGE -- WAKESCENE"

Aerospace Science and Technology, Vol. 13, 2009, pp. 1-11

Wake-vortex advisory systems and modifications of ATC procedures that aim at increasing airport capacity without compromising safety have been developed in recent years. Prior to the introduction of such systems the associated risks must be assessed. The WakeScene (Wake Vortex Scenarios Simulation) Package allows to assess the encounter probability behind different wake-vortex generating aircraft during approach and landing. WakeScene consists of modules that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard area. This manuscript introduces the operating sequence of WakeScene, the employed sub-models and data bases, the simulation environment and evaluation tools together with the so far accomplished validation work. Examples of WakeScene applications and an outlook on further developments of the software package conclude the report.

Holzaepfel, F., Gerz, T. and Baumann, R.

"THE TURBULENT DECAY OF WAKE VORTICES IN THE STABLY STRATIFIED ATMOSPHERE"

AIAA Paper No. 2000-0754, Reno, NV, January 2000

The decay of wake vortices in the stably stratified atmosphere is investigated by means of large eddy simulations. Results of in-situ measurements in the wakes of different aircraft are used to find appropriate initializations for the simulation of wake turbulence in the quiescent atmosphere. Furthermore, cases with weak atmospheric turbulence are investigated. It is shown that the early development of the vortices is not affected by turbulence and develops almost identically as in 2D simulations. In a quiescent atmosphere the subsequent vortex decay is controlled by the interaction of short-wave disturbances, owing to the aircraft induced turbulence, and baroclinic vorticity, owing to stable stratification. When in addition also atmospheric turbulence is present, the long-wave instability is dominantly promoted. For very strong stratification ($Fr < 1$) it is observed that wake vortices may rebound but lose most of their strength before reaching the flight level. Finally, the simulation results are compared to the predictive capabilities of Greene's approximate model.

Holzaepfel, F., Gerz, T. and Baumann, R.

"THE TURBULENT DECAY OF TRAILING VORTEX PAIRS IN STABLY STRATIFIED ENVIRONMENTS"

Aerospace Science and Technology, Vol. 5, No. 2, February 2001, pp. 95-108

The decay of trailing vortex pairs in thermally stably stratified environments is investigated by means of large eddy simulations. Results of in-situ measurements in the wakes of different aircraft are used to find appropriate initializations for the simulation of wake turbulence in the quiescent atmosphere. Furthermore, cases with weak atmospheric turbulence are investigated. It is shown that the early development of the vortices is not affected by turbulence and develops almost identically as in 2D simulations of wake vortices in stably stratified environments. In a quiescent atmosphere the subsequent vortex decay is controlled by the interaction of short-wave disturbances, owing to the aircraft induced turbulence, and baroclinic vorticity, owing to stable stratification. Consequently, vertical vorticity streaks between the vortices are induced which are substantially intensified by vortex stretching and finally lead to rapid turbulent wake-vortex decay. When in addition atmospheric turbulence is also present, the long-wave instability is dominantly promoted. For very strong stratification ($Fr < 1$) it is observed that wake vortices may rebound but lose most of their strength before reaching the flight level. Finally, the simulation results are compared to the predictive capabilities of Greene's approximate model.

Holzaepfel, F., Gerz, T. and Schwarz, C.

"THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS"

Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), June 2011, Berlin, Germany.

Design and performance of the Wake Vortex Prediction and Monitoring System WSVBS are described. The WSVBS has been developed to tactically increase airport capacity for approach and landing on single runways as well as closely-spaced parallel runways. It is thought to dynamically adjust aircraft separations dependent on weather conditions and the resulting wake vortex behavior without compromising safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behavior and respective safety areas. LIDAR monitors the correctness of WSVBS predictions in the most critical gates at low altitude. The WSVBS is integrated in the arrival manager AMAN of DLR. Within 66 days of performance test at Frankfurt airport it was found that the system ran stable and the predicted minimum separation times were correct. The capacity improving concepts of operation could have been used in 75% of the time. From fast-time simulations the eventual capacity gain for Frankfurt was estimated to be 3% considering the real traffic mix and operational constraints in the period of one month. Aircraft separations for landings on single runways have been compared employing the concepts of either heavy - medium weight class combinations or dynamic pairwise separations where individual aircraft type pairings are considered. The consideration of individual aircraft types and their respective wake characteristics may almost double the fraction of time when radar separation could be applied.

Holzaepfel, F., Gerz, T., Frech, M. and Dornbrack, A.

"The Decay of Wake Vortices in the Convective Boundary Layer"

AIAA Paper 99-0984, January 1999, Reno, NV.

The decay of three wake vortex pairs of a B-747 aircraft in a convectively driven atmospheric boundary layer is modelled by means of large-eddy simulations. It is shown that parts of the wake vortices may stay on flight level when updraft velocities of thermals compensate the induced descent speeds of the wake vortices. A situation which is considered as being hazardous. On the other hand, the atmospheric turbulence rapidly deforms the vortices on larger scales, and erodes them simultaneously on smaller scales such that coherent vortical structures are essentially destroyed after 70 seconds. Strip theory calculations are used to illustrate the temporal and spatial development of lift and rolling moments experienced by a following medium weight class B-737 aircraft. Characteristics of the respective distributions are analyzed. Initially, the maximum rolling moments slightly exceed the available roll control of the B-737. After 60 seconds the probability of rolling moments exceeding 50% of the roll control, a value which is considered as a threshold for acceptable rolling moments, has decreased to 1% of its initial probability. Twenty seconds later no rolling moments can be found which exceed the critical roll control level.

Holzaepfel, F., Gerz, T., Frech, M. and Dornbrack, A.

"WAKE VORTICES IN CONVECTIVE BOUNDARY LAYER AND THEIR INFLUENCE ON FOLLOWING AIRCRAFT"

J. Aircraft, Vol. 37, No. 6, November-December 2000, pp. 1001-1007

The decay of three wake vortex pairs of B-747 aircraft in an evolving and convectively driven atmospheric boundary layer is investigated by means of large-eddy simulations (LES). Convective boundary layers are considered hazardous because the updraft velocities of a thermal may compensate the induced descent speed of the vortex pair such that the vortices stall in the flight path. The LES results illustrate that (1) the primary rectilinear vortices are rapidly deformed on the scale of the alternating updraft and downdraft regions; (2) parts of the vortices stay on flight level but are quickly eroded by the enhanced turbulence of the updraft; (3) the longest living sections of the vortices are found in regions of relatively calm downdraft flow which augments their descent. Strip theory calculations are used to illustrate the temporal and spatial development of lift and rolling moments experienced by a following medium weight class B-737 aircraft. Characteristics of the respective distributions are analyzed. Initially, the maximum rolling moments slightly exceed the available roll control of the B-737. After 60 sec. the probability of rolling moments exceeding 50% of the roll control has decreased to 0.009% in a safety corridor around the glide path.

Holzaepfel, F., Gerz, T., Frech, M., Tafferner, A., Koop, I., Smalikho, I., Rham, S., Hahn, K.-U. and Schwarz, C.

"THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS - PART I: DESIGN"

1st CEAS European Air and Space Conference, Berlin, Germany, September 2007, pp. 3383-3390.

The design of the Wake Vortex Prediction and Monitoring System WSVBS is described with all its components and their interaction. The WSVBS has been developed to tactically increase airport capacity for approach and landing on closely-spaced parallel runways. It is thought to dynamically adjust aircraft separations dependent on weather conditions and the resulting wake vortex behavior without compromising safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behavior and respective safety areas. The prediction tools employ a number of conservative aircraft parameter combinations that represent the aircraft weight categories medium and heavy. Predictions of the time when all approach corridors along the final approach do not overlap with safety areas determine aircraft separations for follower aircraft of categories medium and heavy. As a safety net a LIDAR monitors the correctness of WSVBS predictions in the most critical gates at low altitude.

Holzaepfel, F., Gerz, T., Frech, M., Tafferner, A., K pp, F., Smalikho, I., Rahm, S., Hahn, K.-U. and Schwarz C.

"THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS PART I: DESIGN"

Air Traffic Control Quarterly, Vol. 17, No. 4, 2009, pp. 323-346

The design of the Wake Vortex Prediction and Monitoring System WSVBS is described with all its components and their interaction. The WSVBS was developed to tactically increase airport capacity for approach and landing on closely-spaced parallel runways. The WSVBS supports dynamic adjustment of aircraft wake vortex separations dependent on weather conditions and the resulting wake vortex

behavior without compromising safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behavior and respective safety areas. The prediction tools employ a number of conservative aircraft parameter combinations that represent the medium and heavy aircraft weight categories. Safe aircraft separations correspond to times when the predicted safety areas associated with wake vortices generated by leading heavy aircraft cannot overlap the arrival flight corridor. A LIDAR monitors the correctness of WSVBS predictions in the most critical regions at low altitude.

Holzaepfel, F., Gerz, T., Frech, M., Tafferner, A., Kopp, F., Smalikho, I., Rahm, S., Hahn, K.-U. and Schwarz, C.

"THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS PART I: DESIGN"

Air Traffic Control Quarterly, Vol. 17, No. 4, pp. 301-322.

The design of the Wake Vortex Prediction and Monitoring System WSVBS is described with all its components and their interaction. The WSVBS was developed to tactically increase airport capacity for approach and landing on closely-spaced parallel runways. The WSVBS supports dynamic adjustment of aircraft wake vortex separations dependent on weather conditions and the resulting wake vortex behavior without compromising safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behavior and respective safety areas. The prediction tools employ a number of conservative aircraft parameter combinations that represent the medium and heavy aircraft weight categories. Safe aircraft separations correspond to times when the predicted safety areas associated with wake vortices generated by leading heavy aircraft cannot overlap the arrival flight corridor. A LIDAR monitors the correctness of WSVBS predictions in the most critical regions at low altitude.

Holzaepfel, F., Gerz, T., Kopp, F., Stumpf, E., Harris, M., Young, R. and Dolfi-Bouteyre, A.

"STRATEGIES FOR CIRCULATION EVALUATION OF AIRCRAFT WAKE VORTICES MEASURED BY LIDAR"

Journal of Atmospheric and Oceanic Technology, Vol. 20, No. 8, 2003, pp. 1183-1195.

An assessment of different methods for circulation evaluation from lidar measurement data of aircraft wake vortices is performed. The surface integral of vorticity serves as baseline case that is compared to a method that evaluates the lidar line-of-sight velocity midway between the vortices and to another method that calculates radii-averages of circulations derived from tangential velocities. Systematic deviations from nominal circulation are discussed based on analytical vortices. High-resolution numerical simulation data is applied to perform virtual lidar measurements that reproduce, explain, and quantify (i) the frequently observed initial overestimation of circulation and (ii) the scatter of circulation data caused by the genuine variability of wake vortices in the atmospheric boundary layer. The theoretically derived characteristics of the different evaluation methods are verified against lidar data recorded by several lidar teams during the measurement campaign WakeOP, performed in spring 2001 at special airport Oberpfaffenhofen, Germany.

Holzaepfel, F., Hofbauer, T., Darracq, D., Moet, H., Garnier, F. and Gago, C. F.

"ANALYSIS OF WAKE VORTEX DECAY MECHANISMS IN THE ATMOSPHERE"

Aerospace Science and Tech., Vol. 7, Issue 4, June 2003, pp. 263-275

Results of high-resolution numerical simulations of aircraft wake vortex evolution and decay in different regimes and atmospheric conditions are presented. The different cases comprise (i) the near field interaction of a trailing vortex with an exhaust jet, (ii) the evolution of single vortices and counter-rotating vortex pairs in homogeneous isotropic turbulence, as well as (iii) the decay of wake vortices in a turbulent stably stratified atmosphere, and (iv) in a weakly turbulent sheared environment. The different cases are used to analyze common aspects of vortex dynamics and decay mechanisms. In all scenarios the formation of coherent secondary vorticity structures that enclose the primary vortices is observed. These secondary vorticity structures deform and weaken the primary vortices, and in some cases lead to rapid vortex decay. It is shown that the mean swirling flow effectively rearranges and intensifies any secondary vorticity by tilting and stretching. The secondary vorticity may either originate from the turbine jet, ambient turbulence or may be produced baroclinically. Based on the observed phenomena, eleven postulates are established that pinpoint fundamental aspects of the observed decay mechanisms.

Holzaepfel, F., Hofbauer, T., Darracq, D., Moet, H., Garnier, F. and Gago, C. F.

"WAKE VORTEX EVOLUTION AND DECAY MECHANISMS IN THE ATMOSPHERE"

Proceedings 3rd ONERA-DLR Aerospace Symposium, Paris, France, June 2001, pp. S3-2/1-10

Results of high-resolution numerical simulations of aircraft wake vortex evolution and decay in different regimes and atmospheric conditions are presented. The different cases comprise (i) the near field interaction of a trailing vortex with an exhaust jet, (ii) the evolution of single vortices and counter-rotating vortex pairs in homogeneous isotropic turbulence, as well as (iii) the decay of wake vortices in a turbulent stably stratified atmosphere, and (iv) in a turbulent sheared environment. The different cases are used to analyze common aspects of the decay mechanisms. In all scenarios the formation of secondary vorticity structures that enclose the primary vortices is observed. These secondary vorticity structures deform and weaken the primary vortices, and in some cases lead to rapid vortex decay. It is shown that the mean swirling flow effectively intensifies any secondary vorticity by tilting and stretching. The secondary vorticity itself may either stem from the exhaust jet, ambient turbulence or may be produced baroclinically.

Holzaepfel, F., Hofbauer, T., Gerz, T. and Schuman, U.

"AIRCRAFT WAKE VORTEX EVOLUTION AND DECAY IN IDEALIZED AND REAL ENVIRONMENTS: METHODOLOGIES, BENEFITS AND LIMITATIONS"

Proceedings of the EUROMECH Colloquium, No. 412 on Advances in LES of Complex Flows, Munich, Germany, October 4-6, 2000, pp. 293-30.

After a brief introduction of the governing equations and numerical approaches that are used to simulate wake vortices in the atmosphere associated implications and restrictions are discussed. The complex interaction of turbulence and rotation in the vortex core region is not resolved appropriately and is controlled by the sub-grid scale model. A local Richardson number correction for strong streamline curvature effects is proposed that accounts for stabilizing effects of coherent rotation and reduces vortex core growth rate. Real case simulations demonstrate that LES is capable to reproduce complex wake vortex behavior as the spectacular rebound observed at London Heathrow Int'l Airport. Various idealized cases with stably stratified, turbulent, and sheared environments are used to reveal the mechanisms that control vortex decay.

Holzaepfel, F., Hofbauer, T., Gerz, T. and Schumann, U.

"AIRCRAFT WAKE VORTEX EVOLUTION AND DECAY IN IDEALIZED AND REAL ENVIRONMENTS: METHODOLOGIES, BENEFITS AND LIMITATIONS"

Proceedings of the EUROMECH Colloquium, No. 412 on LES of Complex Transitional and Turbulent Flows, Kluwer Press, 200.

After a brief introduction of the governing equations and numerical approaches that are used to simulate wake vortices in the atmosphere associated implications and restrictions are discussed. The complex interaction of turbulence and rotation in the vortex core region is not resolved appropriately and is controlled by the sub-grid scale model. A local Richardson number correction for strong streamline curvature effects is proposed that accounts for stabilizing effects of coherent rotation and reduces vortex core growth rates. Real case simulations demonstrate that LES is capable to reproduce complex wake vortex behavior as the spectacular rebound observed at London Heathrow Int'l Airport. Various idealized cases with stably stratified, turbulent and sheared environments are used to reveal the mechanisms that control vortex decay.

Holzaepfel, F., Kladetzke, J., Amelsberg, S., De Visscher, I. and Winckelmans, G.

"OPERATIONAL SCENARIOS FOR WAKE VORTEX ENCOUNTER SAFETY ASSESSMENT WITH WAKESCENE-D"

CREDOS Report D3-8, March 2009, DLR, Oberpfaffenhofen, Germany.

This report delineates operational scenarios that shall be investigated with WakeScene-D to contribute to the definition of safe separation distances for takeoff and departure and to the required quantitative safety assessment. For this purpose, the report first recapitulates the findings obtained from the analysis of the measurement campaigns EDDF-1 and EDDF-2 and from preliminary Monte Carlo simulations conducted with WakeScene-D. The suggested scenarios can be split into (i) sensitivity analyses and validation cases that shall deepen the understanding of WakeScene-D and the confidence into the software package and into (ii) scenarios serving as a reference representing the current

situation and the target scenarios for crosswind reduced separations and the related safety case. A ranking of the relevance of the various possible scenarios has been established with input from CREDOS partners.

Holzaepfel, F., Kladetzke, J., Amelsberg, S., Lenz, H., Schwarz, C. and De Visscher, I.

"AIRCRAFT WAKE VORTEX SCENARIOS SIMULATION PACKAGE FOR TAKEOFF AND DEPARTURE"

Journal of Aircraft, Vol. 46, No. 2, March-April 2009, pp. 713-717.

The WakeScene-D software package (Wake Vortex Scenarios Simulation Package for Departure) has been developed for comprehensive airspace simulations of take-off and departure. WakeScene-D consists of modules that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard areas. The software package estimates the probability to encounter wake vortices in different traffic and crosswind scenarios using Monte Carlo simulation in a domain ranging from the runway to an altitude of 3000 ft above ground. The operating sequence of WakeScene-D, the employed sub-models and data bases, the simulation environment and evaluation tools together with the so far accomplished validation work are introduced. The current departure situation with a two-minute aircraft separation is compared to (i) a scenario with reduced separations of one minute, (ii) the mitigation effects of crosswind and (iii) the situation prevailing during approach and landing.

Holzaepfel, F., Kladetzke, J., Amelsberg, S., Lenz, H., Schwarz, C. and De Visscher, I.

"AIRCRAFT WAKE VORTEX SCENARIOS SIMULATION FOR TAKE-OFF AND DEPARTURE"

ICAS 2008, Anchorage, AK, Sept. 2008

The WakeScene-D software package (Wake Vortex Scenarios Simulation Package for Departure) has been developed for comprehensive airspace simulations of take-off and departure. WakeScene-D consists of modules that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard areas. The software package estimates the probability to encounter wake vortices in different traffic and crosswind scenarios using Monte Carlo simulation in a domain ranging from the runway to an altitude of 3000 ft above ground. The operating sequence of WakeScene-D, the employed sub-models and data bases, the simulation environment and evaluation tools together with the so far accomplished validation work are introduced. The current departure situation with a two-minute aircraft separation is compared to (i) a scenario with reduced separations of one minute, (ii) the mitigation effects of crosswind and (iii) the situation prevailing during approach and landing.

Holzaepfel, F., Kladetzke, J., Amelsberg, S., Lenz, H., Schwarz, C. and De Visscher, I.

"Aircraft Wake Vortex Scenarios Simulation for Take-Off and Departure"

ICAS 2008-11.8.3, AIAA Paper 2008-8921, September 2008, Anchorage, Alaska.

The WakeScene-D software package (Wake Vortex Scenarios Simulation Package for Departure) has been developed for comprehensive airspace simulations of take-off and departure. WakeScene-D consists of modules that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard area. The software package estimates the probability to encounter wake vortices in different traffic and crosswind scenarios using Monte Carlo simulation in a domain ranging from the runway to an altitude of 3000 ft above ground. The operating sequence of WakeScene-D, the employed sub-models and data bases, the simulation environment and evaluation tools together with the so far accomplished validation work are introduced.

Holzaepfel, F., Misaka, T. and Hennemann, I.

"WAKE-VORTEX TOPOLOGY, CIRCULATION, AND TURBULENT EXCHANGE PROCESSES"

AIAA Paper No. 2010-7992, Toronto, Canada, August 2010.

Large eddy simulations of aircraft wake vortex evolution in various turbulent and stably stratified atmospheric environments have been conducted with two different LES codes. Passive tracers are used to investigate exchange processes between the vortex cores, the vortex oval and its environment as well as redistribution processes along the vortex tubes. A post processing method is employed to identify the vortex center lines even in progressed states of vortex decay where the coherent vortex structure is getting lost. This method allows, for example, analyzing the circulation evolution of vortex rings, establishing statistics of vortex deformation, and revealing the mechanisms of the vortex bursting phenomenon. Vortex bursting is related to the collision of secondary vorticity structures propagating along the vortex lines. In neutrally and weakly stratified environments long-living vortex rings are observed where circulation decay proceeds in three phases. During the initial diffusion phase vortex decay may depend on integral turbulence length scales. On average, the detrainment of a passive tracer from the primary vortices is correlated with circulation decay.

Holzaepfel, F., Stephan, A., Heel, T. and Korner S.

"ENHANCED WAKE VORTEX DECAY IN GROUND PROXIMITY TRIGGERED BY PLATE LINES"

Aircraft Engineering and Aerospace Technology Vol. 88, Issue 2, 2016, pp. 206-214.

Purpose From pilot reports, field measurements and numerical simulations, it is known that wake vortices may persist within the glide path in ground proximity, leading to an increased encounter risk. This paper aims to investigate wake vortex behavior during final approach and landing to understand why landings can be safe nevertheless. Further, it is investigated whether and to which extent the installation of plate lines beyond the runway tails may further accelerate wake vortex decay and thus improve safety by reducing the number of wake vortex encounters.

Holzaepfel, F., Stephan, A., Korner, S. and Misaka, T.

"WAKE VORTEX EVOLUTION DURING APPROACH AND LANDING WITH AND WITHOUT PLATE LINES"

AIAA Paper 2014-0925, January 2014, National Harbor, MD.

Data from numerical simulations and two field measurement campaigns are used to investigate aircraft wake vortex evolution during final approach and landing with and without a plate line. A new hybrid simulation method is employed to capture wake vortex evolution from early roll-up to final decay in ground proximity. Vortex decay is driven by the turbulence of the aircraft wake itself, the interaction of the wake vortices with the ground, the so-called end effects triggered by the sudden loss of lift during touchdown, and it is artificially augmented by a plate line installed a few hundred meters from the runway threshold. The field experiments WakeMUC at Munich airport and WakeOP at special airport Oberpfaffenhofen corroborate and complement the findings of the simulations. The end effects together with an acceleration of the decay in close ground proximity significantly accelerate vortex decay nearby the runway. Since the probability to encounter wake vortices is distinctly increased in ground effect, the described mechanisms ensure the required safety of air traffic operations. Experiments and simulations demonstrate that plate lines appreciably accelerate wake vortex decay and interfere favorably with end effects. This way safety can be further increased during the flight phase with most reported encounters.

Holzaepfel, F., Stephan, A., Tchipev, N., Heel, T., Korner, S. and Misaka, T.

"IMPACT OF WIND AND OBSTACLES ON WAKE VORTEX EVOLUTION IN GROUND PROXIMITY"

AIAA Paper 2014-2470, June 2014, Atlanta, GA.

Data from different numerical simulations and field measurement campaigns are used to investigate aircraft wake vortex evolution in ground proximity. A new hybrid simulation method is employed to capture wake vortex evolution from early roll-up to final decay in ground proximity. The method is applied to investigate effects of very low flight altitudes and the sudden loss of lift during touchdown. The investigations also comprise a parameter study of vortex behavior at different wind directions and strengths (headwind, crosswind, and combinations thereof) where the vortices are generated at a height of one initial vortex separation above ground. Furthermore, it is shown that vortex decay in ground proximity can be accelerated by the installation of plate lines at distances of a few hundred meters from the runway threshold. Field measurement data gathered during the campaigns WakeMUC at Munich airport and WakeOP at special airport Oberpfaffenhofen corroborate and complement the findings of the simulations. Experiments and simulations demonstrate that plate lines appreciably accelerate wake vortex decay and interfere favorably with end effects. This way safety case can be further increased during the flight phase with most reported encounters.

Holzaepfel, F., Tchipev, N. and Stephan, A.

"WIND IMPACT ON SINGLE VORTICES AND COUNTERROTATING VORTEX PAIRS IN GROUND PROXIMITY"

AIAA Paper 2015-3174, June 2015, Dallas, TX.

Wall-resolved large eddy simulations are employed to investigate the behavior of wake vortices and single vortices in ground proximity at a variety of wind conditions. The six considered strengths of wind, ranging between 0.5 and 4 times the initial wake vortex descent speed include practically and theoretically significant wind speeds. A crosswind of 0.5 times the vortex descent speed may lead to windward stall posing a potential hazard to subsequently landing aircraft, whereas theoretical considerations predict that at 4 times the vortex descent speed the rebound of the luff vortex is completely suppressed. The same range of wind speeds is also used to investigate the effects of headwind and diagonal wind to discriminate between effects of environmental turbulence increasing with wind speed and the direction of the wind shear. The study has been complemented by several single vortex computations to differentiate between effects related to the mutual interaction of the vortex pair and the individual vortices with the turbulent boundary layer flow. It is shown that vortex ascent, descent, rebound, and decay characteristics are controlled by (i) the interaction of the vortices with secondary vorticity detaching from the ground and (ii) redistribution of vorticity of the boundary layer which is altering the path of the primary vortices by mutual velocity induction.

Holzaepfel, F., Tchipev, N. and Stephan, A.

"Wind Impact on Single Vortices and Counterrotating Vortex Pairs in Ground Proximity"

Flow, Turbulence and Combustion, Vol. 97, Issue 3, October 2016, pp 829 848, DOI: 10.1007/s10494-016-9729-2

Wall-resolved large eddy simulations are employed to investigate the behavior of wake vortices and single vortices in ground proximity at a variety of wind conditions. The six considered strengths of wind, ranging between 0.5 and 4 times the initial wake vortex descent speed, w_0 , include practically and theoretically significant wind speeds. A crosswind of 0.5 w_0 may lead to windward stall posing a potential hazard to subsequently landing aircraft, whereas theoretical considerations predict that at 4 w_0 the rebound of the luff vortex is completely suppressed. The same range of wind speeds is also used to investigate the effects of headwind and diagonal wind to discriminate between effects of environmental turbulence increasing with wind speed and the direction of the wind shear. The study has been complemented by several single vortex computations to differentiate between effects related to the mutual interaction of the vortex pair and the individual vortices with the turbulent boundary layer flow. It is shown that vortex ascent, descent, rebound, and decay characteristics are controlled by (i) the interaction of the vortices with secondary vorticity detaching from the ground, (ii) the redistribution of vorticity of the boundary layer which is altering the path of the primary vortices by mutual velocity induction, and (iii) the interaction of the vortices with the environmental turbulence.

Hon, K. K. and Chan, P. W.

"APPLICATION OF LIDAR-DERIVED EDDY DISSIPATION RATE PROFILES IN LOW-LEVEL WIND SHEAR AND TURBULENCE ALERTS AT HONG KONG INTERNATIONAL AIRPORT"

Meteorological Applications, Vol. 21, 2014, pp. 74-85.

In aviation meteorology, eddy dissipation rate (EDR) is an internationally-adopted metric for quantifying intensity of low-level turbulence (rapid, irregular headwind fluctuations experienced by an aircraft below 1600 feet/500 m). In this paper, calculations of EDR to the 1/3 power profiles along arrival corridors (07LA, 25RA) of the Hong Kong International Airport (HKIA) were performed over a 45-month period (January to September, 2008-2012) based on radial velocity from a scanning Doppler LIDAR using the azimuthal velocity structure function approach. The quality of the LIDAR-estimated EDR was established by comparison with values calculated from in situ measurements over a 24-month period, which showed that median values of EDR profiles from both sources fell within 0.05 m to the 2/3 power per second of each other in over 90 percent (80 percent) of instances for 07LA (25RA). The performance in threshold-based alerting of low-level turbulence at HKIA was then validated against pilot reports. At alert duration of 10 percent, alerts based on the maximum value of an EDR profile could capture over 90 percent (80 percent) of reported events over 07LA (25RA), while comparable performance with the wind shear and turbulence warning system (WTWS) at HKIA was attainable using suitable alert thresholds. Positive skill, albeit inferior to WTWS, was also observed in the alerting of low-level wind shear (sustained headwind change of 15 knots or above below 1600 feet/500 m) with a hit rate of about 70 percent at alert duration of 10 percent. This study served to establish the value of EDR derived from ground-based remote-sensing instruments e.g. LIDAR in alerting of low-level turbulence for the aviation community.

Hong, J., Toloui, M., Chamorro, L. P., Guala, M., Howard, K., Riley, S., Tucker, J. and Sotiropoulos, F.

"NATURAL SNOWFALL REVEALS LARGE-SCALE FLOW STRUCTURES IN THE WAKE OF A 2.5-MW WIND TURBINE"

Nature Communications, Vol. 5, June 2014, pp. 4216-1 to 4216-9.

To improve power production and structural reliability of wind turbines, there is a pressing need to understand how turbines interact with the atmospheric boundary layer. However, experimental techniques capable of quantifying or even qualitatively visualizing the large-scale turbulent flow structures around full-scale turbines do not exist today. Here we use snowflakes from a winter snowstorm as flow tracers to obtain velocity fields downwind of a 2.5-MW wind turbine in a sampling area of about 36x36 square meters. The spatial and temporal resolutions of the measurements are sufficiently high to quantify the evolution of blade-generated coherent motions, such as the tip and trailing sheet vortices, identify their instability mechanisms and correlate them with turbine operation, control, and performance. Our experiment provides an unprecedented in situ characterization of flow structures around utility-scale turbines, and yields significant insights into the Reynolds number similarity issues presented in wind energy applications.

Hong, Y. and Altman, A.

"STREAMWISE VORTICITY IN SIMPLE MECHANICAL FLAPPING WINGS"

TheJournal of Aircraft, Vol. 44, No. 5, September-October 2007, pp. 1588-1597.

The presence of streamwise vorticity in the vicinity of the wing tip contributes to lift in thin flat plate zero pitch angle flapping wings in quiescent air. In creating flapping wing micro air-vehicles it is desirable to maintain only the mechanical and kinematic complexity that is absolutely necessary to artificially duplicate flapping wing flight. This study quantifies the lift generated from a flapping motion of absolute minimum complexity thought to be capable of generating lift. Using a flapping wing micro air vehicle with wings fabricated in-house, streamwise vortices were identified along the span of wings of various aspect ratios and at numerous different points throughout the flapping cycle under a variety of operating conditions. The lift generated by the flapping mechanism was quantified experimentally using a force transducer and a high-speed camera. Digital particle image velocimetry was used to determine the contributions of streamwise to the total measured lift. Further evidence was found of the importance of the relationship between wing span and flapping frequency in the nature of the formation and shedding of vortices.

Hoogstraten, M., Visser, H. G., Hart, D., Treve, V. and Rooseleer, F.

"IMPROVED UNDERSTANDING OF EN ROUTE WAKE-VORTEX ENCOUNTERS"

Journal of Aircraft, Vol. 52, No. 3, May-June 2015, pp. 981-989.

Wake turbulence can be experienced by aircraft when encountering the wake vortex of another aircraft. The aim of this study is to improve the understanding of the risk posed by en route wake-vortex encounters in the en route flight phase. To quantify this risk, a simulation framework has been conceived that makes use of recorded historical surveillance data and computes the wake-vortex trajectory and decay for each aircraft based on a wake-vortex model. The simulation has been validated and subsequently used to determine the probability of encountering a wake vortex in upper European airspace. The simulation results bear out that a severe wake-vortex encounter can be expected approximately once every 30 days. Three factors have been identified that contribute to the risk of encountering a wake vortex during the en route phase of flight, viz., the characteristics of the exposed or generating aircraft, the encounter geometry, and the prevailing tropopause height in the atmosphere. The combined time evolution of these three factors suggests that the en-route wake-vortex encounter risk may increase in the future. Finally, both short-term and long-term mitigation measures are proposed that can potentially reduce the severity of wake-vortex encounters or even prevent their occurrence.

Hopkins, H.

"VORTEX STUDIES: CLOSING THE GAP"

Jane's Airport Review, Vol. 6, No. 2, March 1994, pp. 27-28

Most of the basic research work has been done in the US, but two studies in Europe have focused on operational questions. The UK's Civil Aviation Authority (CAA) first started vortex reporting by pilots in 1972. A study of data, mainly at London Heathrow from 1982-1990, is now a unique source of day-to-day events, albeit relating to local types and weather. The German research agency DLR has been using

a modified scanning laser doppler anemometer, ranging up to 1000m with elevation accuracy of 0.2 degrees; it was sited 850m in from the easterly thresholds at Frankfurt between parallel runways separated by 518m. The findings are said to be relevant for runways up to 750m apart. Roll rates imposed by vortices can exceed the roll control of an average aircraft - a maximum rate of 15 degrees is typical on approach, which equates to 4m/s at 15m tip distance.

Horn, J. F., Bridges, D. O., Wachspress, D. A. and Rani, S. L.

"IMPLEMENTATION OF A FREE-VORTEX WAKE MODEL IN REAL-TIME SIMULATION OF ROTORCRAFT"

Journal of Aerospace Computing, Information and Communication, Vol. 3, March 2006, pp. 93-114.

Free-vortex wake models are capable of providing an accurate and physically detailed representation of the main rotor wake for flight dynamics simulation. Recent advances in computing power and efficient algorithms have made it feasible to use free wakes for real-time simulation. The CHARM free-vortex wake model was integrated with the GENHEL flight dynamics simulation of the UH-60A helicopter. A high-fidelity wake model was defined by increasing the spatial and temporal resolution of the wake until a converged response was observed, but this baseline model could not execute in real-time. A parametric study was performed to find the best combination of wake parameters to achieve real-time execution with minimal deviation from the baseline model in terms of the frequency and time responses in the pitch and roll axes. A real-time model was found and showed reasonable agreement with the baseline model as compared to a single finite-state inflow model. A parallel implementation of the free-wake model was also investigated. An increase in computational efficiency could be achieved using a distributed processing approach with asynchronous communications.

Horner, M. B., Stewart, J. N., Galbraith, R. A. McD., Grant, I. and Coton, F. N.

"AN EXAMINATION OF VORTEX DEFORMATION DURING BLADE-VORTEX INTERACTION UTILISING PARTICLE IMAGE VELOCIMETRY"

ICAS 1994, Paper No. 3.4.5, September 1994, Anaheim, CA.

The results of a Blade-Vortex Interaction (BVI) study incorporating Particle Image Velocimetry (PIV) are presented. Test cases encompass a variety of intersection geometries, including head-on parallel interactions. Results provide quantified flow visualization images of the flows generated during interactions. The deformation and division of the interaction vortex during head-on interactions is documented. In addition, secondary vortical structures generated during interactions are observed and their effect upon the interaction vortex is examined. All PIV results are examined in the light of understanding gained from previous pressure measurements made from the same BVI facility.

Hornschemeyer, R., Kauertz, S., Haverkamp, S., Neuwerth, G. and Henke, R.

"TIP VORTEX DESTABILIZATION WITH AND WITHOUT WINGLETS"

Proceedings in Applied Mathematics and Mechanics, Vol. 6, 2006, pp. 869-870.

Wake vortices are an inevitable by-product of lift. Another airplane following too closely can be dangerously influenced by induced rolling moments. Consistent adherence to the prescribed safety margins ensures safe flight, however it also obstructs the capacity of large airports. To remedy the expected future capacity problems, research is being carried out world-wide. This paper describes some results of the research work to decrease the hazard of the vortex wake accomplished at the Institute.

Hornschemeyer, R., Neuwerth, G. and Henke, R.

"INFLUENCING AIRCRAFT WING VORTICES"

Flow Modulation and Fluid-Structure Interaction, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 109, 2010, pp. 181-204.

The goal of this project was to gain better understanding of aircraft wake vortices to investigate possibilities to mitigate the hazard posed by these to following aircraft. To this end wind tunnel testing was undertaken in which the vortex wakes of various wings were measured using hot wire anemometry. It was shown that in the near field, the rolling moment induced on a following aircraft can be significantly reduced by introducing additional turbulence into the wake. Another focus point was the investigation into excitation of short-wave instability mechanisms in the vortex wake and their effects in the far field. For these purposes experiments with various models and oscillating control surfaces were conducted in water towing tanks in which the vortex wakes were measured using particle image velocimetry. The results show that for an appropriate multi-vortex system, inherent instabilities can be excited leading to a more rapid vortex decay within the first 30 spans lengths behind the model. The effects of these mechanisms further out in the far field are, however, minimal.

Hornschemeyer, R., Rixen, C., Kauertz, S., Neuwerth, G. and Henke, R.

"ACTIVE MANIPULATION OF A RECTANGULAR WING VORTEX WAKE WITH OSCILLATING AILERONS AND WINGLET-INTEGRATED RUDDERS"

New Results in Numerical and Experimental Fluid Mechanics VI, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 96, 2008, pp. 44-51.

This paper presents results of experimental investigations regarding the vortex wake of a rectangular wing with winglets in a water towing tank. The model comprises ailerons and additional rudders, which are integrated into the winglets. The ailerons and the rudders can oscillate around a static deflection to excite inherent short-wavelength instabilities in the vortex system. The Particle Image Velocimetry method is used to investigate the vortex wake up to about 40 spans behind the model. The results show that, depending on the preselected aileron and rudder deflections, an oscillation of correctly chosen frequency leads to a faster decay of the vortex wake in comparison to the static case.

Horstmann, J. T., Henningsson, P., Thomas, A. L. R. and Bomphrey, R. J.

"WAKE DEVELOPMENT BEHIND PAIRED WINGS WITH TIP AND ROOT TRAILING VORTICES: CONSEQUENCES FOR ANIMAL FLIGHT FORCE ESTIMATES"

PLoS ONE, Vol. 9, Issue 3, March 2014, pp. e91040-1 to e91040-9.

Recent experiments on flapping flight in animals have shown that a variety of unrelated species shed a wake behind left and right wings consisting of both tip and root vortices. Here we present an investigation using Particle Image Velocimetry (PIV) of the behavior and interaction of trailing vortices shed by paired, fixed wings that simplify and mimic the wake of a flying animal with a non-lifting body. We measured the flow velocities at five positions downstream of two adjacent NACA 0012 airfoils and systematically varied aspect ratio, the gap between the wings (corresponding to the width of a non-lifting body), angle of attack, and the Reynolds number. The range of aspect ratios and Reynolds number were chosen to be relevant to natural fliers and swimmers, and insect flight, in particular. We show that the wake behind the paired wings deformed as a consequence of the induced flow distribution such that the wingtip vortices move downwards while the root vortices twist around each other. Vortex interaction and wake deformation became more pronounced further downstream of the wing, so the positioning of PIV measurement planes in experiments on flying animals has an important effect on subsequent force estimates due to rotating induced flow vectors. Wake deformation was most severe behind wings with lower aspect ratios and when the distance between the wings was small, suggesting that animals that match this description constitute high-risk groups in terms of measurement error. Our results, therefore, have significant implications for experimental design where wake measurements are used to estimate forces generated in animal flight. In particular, the downstream distance of the measurement plane should be minimized, notwithstanding the animal welfare constraints when measuring the wake behind flying animals.

Hoshizaki, H., Conti, R. J., Anderson, L. B., Redler, K. O., Meyer, J. W., McLean, W. J. and Cassidy, P. E.

"STUDY OF HIGH ALTITUDE AIRCRAFT WAKE DYNAMICS: TASK 1, PROBLEM DEFINITION"

DOT-TST-90-3, December 1972, Lockheed Research Laboratory, Palo Alto, CA.

The important features of chemically reacting aircraft wakes have been identified. The aircraft wake is modeled in terms of the jet regime (wake age about 10 seconds), vortex regime (wake age about 100 seconds), and the wake dispersion regime (wake age about 100 seconds). The important thermochemical reactions were found to take place in the jet regime.

Hoshizaki, H., Redler, K. O., Meyer, J. W., Conti, R. J. and Anderson, L. B.

"STUDY OF HIGH ALTITUDE AIRCRAFT WAKE DYNAMICS, MODEL DEVELOPMENT"

DOT-TST-73-5, January 1973, Lockheed Palo Alto Research Lab., Palo Alto, CA

A chemically-reacting wake model computer program has been formulated. The wake model program computes the wake height and width from the jet engine nozzle to the point in time where

aerodynamic perturbations are small. The program also predicts the detailed chemical reactions that occur in the jet exhaust flow field.

Houbolt, J. C.

"ATMOSPHERIC TURBULENCE"

AIAA Journal, Vol. 11, No. 4, April 1973, PP. 421-437.

Atmospheric turbulence and its influence on the flight and design of aircraft is reviewed. Coverage includes accidents and costs incurred as a result of turbulence, the mechanisms of turbulence measurements that are made, aircraft response and design procedures due to turbulence encounters, and loads alleviation devices. Basic research notions associated with the interpretation of turbulence data, some of which are controversial, and areas of weakness, are also discussed.

Houbolt, J. C.

"AIRCRAFT RESPONSE TO TURBULENCE INCLUDING WAKES"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 509-522

The nature of atmospheric turbulence and the means for establishing aircraft response is reviewed, both from discrete-gust and spectral interpretations. Application is then made to the situation of wake turbulence encounter to show the nature and magnitude of the loads that result. Specific cases are treated, with encounters perpendicular to and parallel to the wake, to bring out the main parameters that are significant. General relations are also developed to show how the wake 'gust' forces on the encountering airplane are related to the lift on the airplane generating the wake. It is shown that normal loads in excess of 2 g's may be produced by a perpendicular encounter of a wake vortex, and that uncontrollable rolling moments may be caused by encounters along the axis of a vortex.

Houston, S. S. and Brown, R. E.

"ROTOR-WAKE MODELING FOR SIMULATION OF HELICOPTER FLIGHT MECHANICS IN AUTOROTATION"

Journal of Aircraft, Vol. 40, No. 5, September-October 2003, pp. 938-945.

Rotorcraft flight mechanics simulations typically use finite-state induced velocity models to mimic the effect of the rotor wake on blade loads. However, with recent developments in computational methods coupled flight mechanics and comprehensive rotor-wake analyses have become more tractable. This paper compares results from a finite-state induced velocity model with a vorticity transport wake model that computes the flow field in a domain around the aircraft. The study focuses on flight mechanics in autorotation. Simple parameter estimation using three- and five-state induced velocity model structures facilitates interpretation of the vorticity transport induced velocity field as well as providing a direct comparison with the finite-state model. Comparisons of performance, trim, and control response indicate that there is little difference between the two models where the

autorotative descent is shallow. However, as airspeed reduces the descent angle steepens, and clear discrepancies become apparent. These are directly related to a single parameter in the finite-state model. It is concluded that finite-state models are adequate for much of the autorotation regime, but for low speeds in steep descents the improved resolution of the rotor inflow provided by more comprehensive rotor-wake models might be essential.

Howard, K. B. and Guala, M.

"CHARACTERIZING THE EFFECTS OF INFLOW ON A 2.5 MW RESEARCH UTILITY TURBINE"

AIAA Paper 2016-1400, January 2016, San Diego, CA.

A series of field experiments conducted at the Eolos wind research facility studied the impact of inflow conditions on a utility scale wind turbine. This research strives to answer (i) how wind at various elevations influences the turbine's power production and (ii) what effects wind gusts have on individual blade loading. The Eolos test facility is operated by the University of Minnesota's Saint Anthony Falls Laboratory (SAFL) and is home to a 2.5-megawatt (MW) Clipper Liberty C96 wind turbine and meteorological tower. In addition to the flow information provided by the meteorological tower, on site we have a WindCube LIDAR wind profiler, allowing wind data to be gathered at any desired location on site. The wind data coupled with the time history of the power output and ten strain gauges located in each of the blades provided us with the ability to track the effect of wind gusts on the power production as well as the blade structural loading. We hope this information along with the correlation of wind at different elevations to the power output will help the wind turbine controls community mitigate fatigue loads while maintaining or increasing power production.

Howe, M. S.

"ON THE SCATTERING OF SOUND BY A RECTILINEAR VORTEX"

Journal of Sound and Vibration, Vol. 227, Issue 5, November 1999, pp. 1003-1017.

A re-examination is made of the two-dimensional interaction of a plane, time-harmonic sound wave with a rectilinear vortex of small core diameter at low Mach number. Sakov and Ford and Smith have independently resolved the 'infinite forward scatter' paradox encountered in earlier applications of the Born approximation to this problem. The first order scattered field (Born approximation) has nulls in the forward and back scattering directions, but the interaction of the wave with non-acoustically compact components of the vortex velocity field causes wavefront distortion, and the phase of the incident wave to undergo a significant variation across a parabolic domain whose axis extends along the direction of forward scatter from the vortex core. The transmitted wave crests of the incident wave become concave and convex, respectively, on opposite sides of the axis of the parabola, and focusing and defocusing of wave energy produces corresponding increases and decreases in wave amplitude. Wave front curvature decreases with increasing distance from the vortex core, with the result that the wave amplitude and phase are asymptotically equal to the respective values they would have attained in the absence of the vortex. The transverse acoustic dipole generated by translational motion of the

vortex at the incident wave acoustic particle velocity, and the interaction of the incident wave with acoustically compact components of the vortex velocity field, are responsible for a system of cylindrically spreading, scattered waves outside the parabolic domain.

Howe, M. S.

"LECTURES ON THE THEORY OF VORTEX-SOUND"

Lecture Notes in Physics, Vol. 586, 2002, pp. 31-111

The theory of vortex sound is introduced. From Lighthill's acoustic analogy, it is shown how vorticity and entropy fluctuations can be seen as sources of sound. The use of the compact Green's functions is introduced to compute the vortex sound. As an example of the method presented, this theory is applied to pressure transients generated by high-speed trains.

Hrynuk, J. T., Van Luipen, J. and Bohl, D.

"FLOW VISUALIZATION OF A VORTEX RING INTERACTION WITH POROUS SURFACES"

Physics of Fluids, Vol. 24, 2012, pp. 037103-1 - 037103-17.

The interaction of vortex rings of constant Reynolds number with porous surfaces composed of wire meshes of constant open area, i.e., surface porosity, but variable wire diameter is studied using flow visualization. The results indicate that several regimes of flow behavior exist in the parameter space investigated. The vortex ring passes through and immediately reforms downstream of the surface for porous surfaces with small wire mesh diameters. The transmitted vortex ring has the same diameter, but lower convection speed and circulation than the pre-interaction vortex ring. For these cases, secondary vortex rings are formed on the upstream side of the porous surface that move upstream away from the screen. As the wire diameter of the porous surface is increased, smaller sub-scale vortical structures are formed on the transmitted vortex ring as it passes through the surface. The spatial scale of these structures is dependent on the diameter of the mesh wire. The vortex ring is disrupted but is able to reform downstream when these structures are small compared to the scale of the vortex ring. When these structures are large enough the transmitted vortex ring is disrupted and does not reform. The results indicate that the dynamics governing the vortex ring/mesh surface interaction are dependent not only on the strength of the vortex ring and the porosity of the surface, as previously thought, but also on the length scales (i.e., the diameter and spacing of the wire mesh) of the porous surface.

Hsiao, C.-T. and Pauley, L. L.

"STUDY OF TIP VORTEX CAVITATION USING NAVIER-STOKES COMPUTATION AND BUBBLE DYNAMICS MODEL"

Journal of Fluids Engineering, Vol. 121, March 1999, pp. 198-204.

The Rayleigh-Plesset bubble dynamics equation coupled with the bubble motion equation developed by Johnson and Hsieh was applied to study the real flow effects on the prediction of cavitation inception in tip vortex flows. A three-dimensional steady-state tip vortex flow obtained from a Reynolds-Averaged Navier-Stokes computation was used as a prescribed flow field through which the bubble was passively convected. A 'window of opportunity' through which a candidate bubble must pass to be drawn into the tip-vortex core and cavitate was determined for different initial bubble sizes. It was found that bubbles with larger initial size can be entrained into the tip-vortex core from a larger window size and also had a higher cavitation inception number.

Hsiao, C.-T. and Pauley, L. L.

"NUMERICAL STUDY OF THE STEADY-STATE TIP VORTEX FLOW OVER A FINITE-SPAN HYDROFOIL"

Journal of Fluids Engineering, Vol. 120, June 1998, pp. 345-353.

The flow over a finite-span hydrofoil creating a tip vortex was numerically studied by computing the full Navier-Stokes equations. A good agreement in pressure distribution and oil flow pattern was achieved between the numerical solution and available experimental data. The steady-state roll-up process of the tip vortex was described in detail from the numerical results. The effect of the angle of attack, the Reynolds number, and the hydrofoil planform on the tip vortex was investigated. The axial and tangential velocities within the tip-vortex core in the near-field wake region were greatly influenced by the angle of attack. A jet-like profile in the axial velocity was found within the tip-vortex core at high angle of attack, while a wake-like profile in the axial velocity was found at low angle of attack. Increasing the Reynolds number was found to increase the maximum axial velocity, but only had a slight impact on the tangential velocity. Finally, a swept hydrofoil planform was found to attenuate the strength of the tip vortex due to the low-momentum boundary layer traveling into the tip vortex on the suction side.

Hsiao, F.-B., Cheng, C.-Z., Liu, W.-J. and Hsu C.-C.

"EXPERIMENTAL STUDY OF TURBULENT WAKE FLOW DEVELOPMENT BEHIND A FINITE WING WITH HIGH ANGLE OF ATTACKS"

ICAS 2002, Sept. 2002, Toronto, Canada, pp. R1-R24.

The experimental approaches are employed to investigate the wake development of finite wing with aspect ratio 3. The stream-wise and transverse velocities in the wake region are measured by the X-shaped hotwire. In the present experimental results, the wake of the finite wing in the near field could be divided into two parts in the span-wise direction. One region is with the same behaviors as those of 2-D wake and the other is affected by the wing-tip vortex. In the 2-D region, the flow field is obviously affected by the downwash. By the comparison the downwash rates of experimental results and those by theoretical analysis, a good consistence could be found. The similarity distribution of mean velocity and root-mean-square velocity could also be observed in the region. Comparing the maximum defective velocity, we found it to be proportional to one over the square root of the distance, which is

compatible with what happens in the 2-D turbulent wake. In the 3-D region, the low-pressure region will form as the result of the development of the wing tip vortices to the downstream. Hence it will suck the fluid upstream and the average velocity measured will be larger than that of free stream. According to the downstream evolution of velocity contours, the development of trailing vortices could be divided into growing, saturating, and decaying processes.

Hsu, T.-M. and Wu, J. C.

"THEORETICAL AND NUMERICAL STUDIES OF A VORTEX-AIRFOIL INTERACTION PROBLEM"

AIAA Paper No. 1986-1094, Atlanta, GA, May 1986

Three different approaches have been utilized to study the vortex-airfoil interaction problem: a theoretical approach, a simplified vortical flow numerical approach, and a fully viscous numerical approach. In the first two approaches, a viscous theorem of aerodynamics is successfully utilized to identify and to assess the individual contributions to unsteady aerodynamic forces from various vortical flow components in attached interaction flow fields. In the fully viscous study, various important features of laminar and turbulent interactions in both attached and separated flows are examined through the numerical solution of the Navier-Stokes equations. The three approaches represent different levels of approximation and are utilized together to establish a comprehensive understanding of the problem. Along with the study of the vortex-airfoil interaction problem, several new schemes are developed for unsteady flow computations. New formulas are derived for computing the unsteady flow trailing edge conditions. A new, highly efficient, iteration scheme for solving the Navier-Stokes equations in high Reynolds flows is established.

Hu, G. H. and Newman, S. J.

"A FULL-SPAN FREE-WAKE MODEL USING CIRCULAR-ARC VORTEX ELEMENTS AND INCORPORATING ROTOR TRIM ANALYSIS"

Proceedings of the Institution of Mechanical Engineering, Part G: Journal of Aerospace Engineering, Vol. 220, No. 2, 2006, pp. 145-163.

An analytic method incorporating a free-wake analysis with a rotor trim algorithm is developed for predicting rotor wake geometry and blade loading distribution for a helicopter in hover and forward flight. The wake model of this method is based on a multi-filament full-span free wake, using sophisticated circular-arc vortex elements. The blade model is based on the second-order lifting line theory to improve the calculation of three-dimensional tip effects. A rotor trim method is given, based on the finite-difference approximation of the blade flapping motion and the Jacobian matrix. This is subsequently coupled into the free-wake model. In order to demonstrate the capability of the coupled method, comparisons between the calculated results and the available experimental data of the rotor blade flapping motion for a model rotor are presented covering conditions from hover through forward flight. The free-wake geometry and the blade loading distribution at a low advance ratio are calculated

for the H-34 helicopter rotor, and the blade loading distribution is compared with both the measured data and calculated results based on the undistorted wake.

Hu, X. and Zhang, G.

"INVESTIGATION OF LAMB-OSEEN VORTEX EVOLUTION AND DECAY IN GROUND PROXIMITY WITH OBSTACLE"

Journal of Fluids Engineering, Vol. 141, January 2019, pp. 011203-1 to 011203-9.

The physical mechanism for the evolution and decay of Lamb-Oseen vortex pair in ground proximity with an obstacle has been investigated in detail by adopting the large eddy simulation (LES). In the present research, we mainly focus on the vortex evolution and decay mechanism in ground proximity with obstacle, so we chose one fixed height of the obstacle case ($h_{sub 0} = 0.5 (b_{sub 0})$) to investigate, and the obstacle is placed transversally to the axis of the primary wake to be analyzed. The trajectories of the primary wake-vortex cores and the circulation profiles, as well as the distribution of the tangential velocity on different axial positions, have been specifically captured and analyzed. The 'stroke' 'claw,' and 'ivory' vortices have been newly found and defined at the initial evolution stage, and they subsequently begin to harshly wind and rotate with the primary vortex. A flow structure with double helix conical shapes of the primary vortex has been found in the obstacle case. The pressure waves along the vortex axis have also been analyzed in detail. The wake-vortex on each side would be pulled in opposite axial directions and eventually pinched off at the upper surface of obstacle. Moreover, it has also been newly found that the trajectories of the wake-vortex in longitudinal directions at different axial distances away from the obstacle will experience two kinds of motion: only descending and rebounding after descending. Results obtained in this study provide a better understanding of mechanisms for the interaction of wake-vortex and the obstacle.

Huang, A.

"WAKES OF ROTORCRAFT MANEUVERING IN GROUND EFFECT"

Georgia Inst. of Technology, Atlanta, GA, 2001

The aerodynamic characteristics of rotorcraft maneuvering in ground effect are investigated to better understand and quantify the flow field structures and unsteadiness associated with various in ground effect flight conditions. The computational modeling to simulate in ground effect in hover and forward flight is being developed. These prediction models will be refined and validated with experimental results. Experimental investigations will involve flow visualization, velocity, pressure, and loads measurements aimed at examining the airflow and wake behavior associated with in ground effect. A literature study of the past research pertaining to ground effect flows has been conducted, including influences on the flow fields, rotor induced velocity, force and moment variations, tip vortex geometry, and ground vortex formation due to the ground. A simple analytical calculation has been performed to estimate the time scales for the blade tip vortex to reach the ground and recirculate back to the rotor.

For robust prediction models to exist, a good agreement between measured, computed, and analytical results is essential.

Huang, J. F., Zhou, Y. and Zhou, T.

"THREE-DIMENSIONAL WAKE STRUCTURE MEASUREMENT USING A MODIFIED PIV TECHNIQUE"

Experiments in Fluids, Volume 40, Issue 6, June 2006, pp. 884-896

Three-dimensional vortical structures have been measured in a circular-cylinder wake using particle imaging velocimetry (PIV) for the Reynolds number range of 2000 to 10,000. The PIV was modified, compared with the conventional one, in terms of its light sheet arrangement to capture reliably streamwise vortices. While in agreement with previous reports, the presently measured spanwise structures complement the data in the literature in the streamwise evolution of the near-wake spanwise vortex in size, strength, streamwise and lateral convection velocities, shedding new light upon vigorous interactions between oppositely signed spanwise structures. The longitudinal vortices display mushroom patterns in the (x, z) -plane in the immediate proximity to the cylinder. Their most likely inclination in the (x, y) -plane is inferred from the measurements in different (x, z) planes. The longitudinal vortices in the (x, z) -plane show alternate change in sign, though not discernible at $x/d > 15$. They decay in the maximum vorticity and circulation rapidly from $x/d = 5$ to 10, and are further compared with the spanwise vortices in size, strength and rate of decay.

Huang, M.-J.

"DIFFUSION VIA SPLITTING AND REMESHING VIA MERGING IN VORTEX METHODS"

International J. for Numerical Methods in Fluids, Vol. 48, June 2005, pp. 521-539

The technique of splitting a fat vortex element (with a core width larger than some threshold) into some thin ones in order to fix the convergence problem of the core-spreading vortex methods is convenient and efficient. In particular, it keeps the method purely Lagrangian. In the present investigation, the splitting process is further viewed as part of the physical diffusion process. A new splitting method in which several weaker child vortices surround a thinned but still strong parent vortex is proposed. It is found that because of the survival of the parent vortex, the error arising from the splitting events can be largely reduced. The computational amount on the other hand is kept reasonably large by merging similar and close-by vortices. The merging scheme designed herein not only involves fewer restrictions but also allows merging vortices of opposite rotations through the viewpoint of remeshing. The validity and accuracy of these techniques, proposed particularly for simulations undergoing lots of splitting and merging events, are verified by successfully simulating the interactions between two Burgers vortices under an external straining field.

Huang, R. F. and Lee, H. W.

"TURBULENCE EFFECT ON FREQUENCY CHARACTERISTICS OF UNSTEADY MOTIONS IN WAKE OF WING"

AIAA Journal, Vol. 38, No. 1, January 2000, pp. 87-94

The influences of the freestream turbulence intensity on the frequency characteristics of the instability wave and vortex shedding in the wake of a NACA 0012 wing model are studied experimentally. The functional relationships among the Strouhal, Roshko, and Reynolds numbers in the viscous-effect-dominated and the inertial-effect-dominated regimes are obtained. The freestream turbulence has apparent effect on the Strouhal and Roshko numbers in the regimes of instability wave and laminar and subcritical vortex-shedding modes that are obtained at low Reynolds numbers. However, at large Reynolds numbers in the supercritical vortex-shedding mode, particularly at large angles of attack, the effect of freestream turbulence intensity on the frequency selection is not significant. For the instability wave, the Roshko number decreases with the increase of freestream turbulence and then approaches constant values when the freestream turbulence intensity is larger than a critical value between 0.45 and 0.5%. However, the Strouhal number of the vortex shedding of laminar and subcritical modes increases significantly with an increase of turbulence intensity and then decreases when the freestream turbulence intensity is larger than a critical value between 0.45 and 0.5%. The change of the characteristic surface flow modes may contribute to the dominant mechanism of the existence of critical freestream turbulence intensity.

Huang, S.

"COMPARISON OF RAPID UPDATE CYCLE (RUC) MODEL CROSSWINDS WITH LIDAR CROSSWIND MEASUREMENTS AT ST. LOUIS LAMBERT INTERNATIONAL AIRPORT"

Proc.13th Conference on Aviation, Range and Aerospace Meteorology, New Orleans, LA, January 2008

Wake turbulence from departing and landing aircraft pose a safety hazard, including aircraft operating on Closely Spaced Parallel Runways (CSPRs). Aircraft separation standards are imposed to mitigate this potential risk. The FAA and NASA are sponsoring a development program for establishing wind-dependent procedures for improved departure operations that safely reduce spacing restrictions to allow increased airport operating capacity. These procedures are referred to collectively as Wake Turbulence Mitigation for Departures (WTMD). An important component of WTMD is a Wind Forecast Algorithm (WFA) being developed by MIT Lincoln Laboratory which predicts when runway crosswinds will persistently remain favorable for WTMD procedures. For winds up to 300 m AGL (the nominal height at which aircraft departing from parallel runways diverge and alternate forms of separation standards are applied), the algorithm relies heavily on the NOAA/NCEP Rapid Update Cycle (RUC) Model forecasts at the 2-to-4-hour time horizon. The performance suitability of RUC wind forecasts for this application is investigated. RUC crosswinds are compared with LIDAR measurement data collected at St. Louis Lambert International Airport (STL) in 2004 and 2006-2007. The results show that the RUC crosswinds generally correlate well with LIDAR measurements, with a mean difference of 0.4 m/s (s.d. 1.3-2.5 m/s) for both the RUC initialization data and the RUC forecast data. No significant degradation was observed at the longer 4-hour RUC forecast horizon, and the choice of RUC horizontal resolution from 40 to 13 km does not greatly affect the RUC crosswind estimation accuracy. On the other hand, the RUC crosswind accuracy decreases with height and frequent wind direction change. The primary

reliability concern was found to occur during rapidly changing wind conditions associated with wind field discontinuities, such as during situations of convective outflow or synoptic scale frontal passages. Overall, our comparison of the RUC and LIDAR crosswinds at STL suggests that the RUC forecast can be a reliable source for obtaining crosswinds for the WFA. Future studies will include airports (e.g., San Francisco International Airport) whose local winds are more significantly affected by regional- or local-scale effects, such as thermally induced circulations (land-sea breezes, etc.) or topographical wind channeling.

Huang, S., Shen, G., Konrath, R., von Carmer, C. F. and Jurgen, K.

"EXPERIMENTAL INVESTIGATION OF INFLUENCE OF JETS ON AIRCRAFT WAKE VORTICES"

Acta Aeronautica et Astronautica Sinica, Vol. 31, No. 5, May 2010, pp. 899-908.

Wake vortices, especially large-scale tip vortices generated by airplanes, are hazardous for following aircraft. This article tries to explore a way to accelerate wake vortex decay through the jets spouted out of the aeroengine. In the experiment, a simplified aircraft model (with tail wing) is employed to construct a 4-vortex wake system consisting of a pair of tip vortices and a pair of counter rotating tail plane vortices. Without external disturbances, effects of vortices generated by the tail plane with different configurations acting on tip vortices differ, some tail plane vortices can lead to the acceleration of tip vortex disintegration, while others cannot. The influence of jets with different intensities on different 4-vortex systems is studied. As a contrast, a 2-vortex system (without tail wing) and without jets are also observed. The experiment is carried out in a water towing tank. A stereo particle image velocimetry (SPIV) system is employed to observe and measure a series of sections which are perpendicular to the towing direction and distributed uniformly between the tailing edge of the main wing and the position of 45 spans downstream. The result indicates that, when the jet is acting on the vortex directly, the effect depends on the original distance and relative strength between them; when the jet is acting on the overall 4-vortex system, the interruption caused by the jet can accelerate the destruction of various 4-vortex systems to a certain degree. The key is how to use jets to optimize the interaction mechanism of disturbance to the tip vortex, rather than merely the intensity of jets.

Huang, W. and Agarwal, R. K.

"CFD ANALYSIS OF TANDEM WIND TURBINES USING A ROTATING DISK MODEL"

AIAA Paper 2017-4071, June 2017, Denver, CO.

The goal of this study is to develop a numerical model to study the performance of two wind turbines operating in tandem at various tip-speed-ratios. A simplified model based on the rotating actuator disk method is developed to replace the spinning blades with two rotating actuator disks on an axisymmetric model. The computations for this model are performed using the CFD solver ANSYS-FLUENT. The results of computations are compared using the wind tunnel data. It is shown that this

simplified model can provide the power coefficient for the tandem wind turbine in good agreement with the experimental data, while maintaining the computational simplicity.

Huang, X., Igarashi, H., Durbin, P. and Hu, H.

"WIND TUNNEL EFFECTS ON WINGTIP VORTICES"

AIAA Paper No. 2010-0325, January 2010, Orlando, FL.

The influence of wind tunnel boundaries on a wing tip vortex is studied experimentally and by computation. Computations show that that vortex is like that which would exist without tunnel walls. The experimental data are corrected for meandering. Then computations are in close agreement to data. A computation with the wall moved closer to the tip shows the primary effect to be displacement of the vortex core by the image effect.

Hubbard, H. B.

"TERMINAL AIRSPACE/AIRPORT CONGESTION DELAYS"

Interfaces, Vol. 8, February 1978, pp. 1-14.

Methods of reducing airport congestion delays are discussed, with particular attention given to an FAA-sponsored program at Chicago's O'Hare Airport. Selection of low-delay runway configurations for the existing wind and weather conditions is found to reduce inbound holding delays by about two to three minutes per arrival. In addition, wake vortex detection systems have been tested to reduce in-trail separations when the wake vortices do not present a problem. More complete real-time air traffic monitoring may also aid in reducing delays.

Hubbard, S. J. and Marquis, A. J.

"INVISCID EFFECTS OF THIN SHEAR LAYERS ON FOUR-VORTEX SYSTEMS"

Journal of Aircraft, Vol. 42, No. 2, March-April 2005, pp. 391-401

The alleviation of the wake vortex hazard by, for example, promoting vortex instability during aircraft landing and takeoff offers the possibility of increased airport capacity for relatively little cost. The interaction of a vortex pair with a thin shear layer using potential flow methods is extended in this paper to shear-layer interactions with more realistic four-vortex systems. Vortex trajectories resulting from encounters with weak and strong shear layers are studied, and the behavior observed is discussed. The effect of the vortex/shear-layer interactions on the robustness of instability mechanisms of four-vortex systems is discussed in relation to the computed trajectories. The computational method enables the salient features of the vortex/shear interactions to be captured in short periods of CPU time using modest processing power. It is concluded that instability mechanisms that utilize the cooperative instability between vortex pairs on either side of the wake are most likely to survive shear-layer interactions.

Huber, H. and Polz, G.

"STUDIES ON BLADE-TO-BLADE AND ROTOR-FUSELAGE-TAIL INFERENCES"

Aircraft Engineering, Vol. 55, No. 10, October 1983, pp. 2-12

The paper focuses on some specific areas of interactional aerodynamics. The first major problem is the blade-to-blade vortex interaction phenomenon, where the unsteady pressure fluctuations, due to the vortices impact, result in highly impulsive blade loadings, excessive dynamic hub forces/moments, and impulsive noise signatures. The paper describes Messerschmitt-Bolkow-Blohm's analytical modelling techniques, including prescribed-contracted-wake analysis and free-wake models. Second, the interactional aerodynamic flow from the fuselage to the rotor blades is treated. Due to flow displacement effects around the fuselage contour, large upwash and downwash components can be produced, resulting in significant changes of the local angle of attack within the rotor disc plane. Third, interference flow effects between the rotor head and fuselage to the tail area are investigated. The wake pattern results in a reduction of the steady flow pressure and in reductions of the vehicle stability characteristics. Significant unsteady components in the wake flow may cause substantial structural loading and severe aircraft vibrations.

Huberson, S. and Daube, O.

"NUMERICAL SIMULATION OF VORTEX FLOWS"

Lecture Notes in Physics, Vol. 555, 2000, pp. 18-39

This paper presents a selection of numerical methods among the most currently used to solve the Navier Stokes equation in a vorticity formulation. The paper focuses on the connection that exists between vorticity boundary condition and the divergence free condition. The different methods have been cast in two classes: the methods which are based on divergence free approximations of the vorticity fields, and those which use a correction procedure to satisfy this constraint. For both classes, the respective advantages of Eulerian grid methods and Lagrangian methods are briefly discussed.

Huberson, S., Rivoalen, E. and Voutsinas, S.

"VORTEX PARTICLE METHODS IN AEROACOUSTIC CALCULATIONS"

Journal of Computational Physics, Vol. 227, 2008, pp. 9216-9240.

The connection between vortex particle methods and aeroacoustics is considered within the framework of Lighthill's acoustic analogy which allows to decouple the flow from noise propagation. For the flow, techniques such as tree-algorithms and the particle-mesh method are brought together with the aim to achieve the best possible performance in view of analyzing complex problems. The flow results are then input to the acoustic wave equation which is solved in integral form. It will involve monopole, dipole and quadrupole terms which can be successively integrated. The significance of such

an approach is first demonstrated in two problems, both related to vortex-solid interactions. The first is a generic one and considers the interaction of a vortex filament interacting with a sphere while the second considers helicopter noise as an example of a complex engineering set-up.

Huebsch, W. W. and Lewellen, D. C.

"SENSITIVITY STUDY ON CONTRAIL EVOLUTION"

AIAA Paper No. 2006-3749, San Francisco, CA, June 2006

It has become increasingly clear in recent years that under certain conditions, aircraft contrails will persist and grow into significant cloud cover that might otherwise be confused with natural cirrus. The projected large increases in air traffic in the coming decades and potential impact of increased cloud cover on global climate change has led to a growing realization of the importance of understanding the formation, properties, and effects of persistent contrails. A preliminary sensitivity analysis on contrail evolution out to 1000 seconds has been performed using 3-D high-resolution large-eddy simulations to solve the wake and plume development, coupled with a binned ice microphysics model. Effects of both atmospheric and aircraft parameters are investigated. It is shown that the use of binned microphysics can have a significant impact on the prediction for the contrail evolution. The atmospheric parameters include the relative humidity with respect to ice, atmospheric turbulence levels, ambient stratification, and wind shear. The aircraft parameters investigated include the ice crystal emission index and the engine placement. The results of the sensitivity analysis shed light on the relative importance of ambient and aircraft parameters on contrail growth. The aircraft wake dynamics in the first few minutes can have profound effects on the properties of the resulting persistent contrails. This occurs both through its governing of the initial plume dispersion and through the loss of a significant fraction of the ice crystals due to adiabatic heating in the falling wake plume, even for large ambient supersaturation levels.

Huenecke, K.

"EUROPEAN INVESTIGATIONS ON WAKE VORTEX PHENOMENA"

Seventh Conference on Industrial Technologies, and Proceedings of 3rd European Commission Aero Days Conference, Toulouse, France, October 1997, *Nouvelle Revue d'Aeronautique et d'Astronautique*, No. 2, March - April 1998, pp. 112-115.

A survey is presented of the range of European research activities conducted to date to deepen understanding of the wingtip vortex wake phenomenon associated with large transport aircraft. Such wakes pose a danger to smaller aircraft during landing approaches, especially when separation between aircraft must be minimized at busy airports. Attention is given to CFD prediction methods and lidar wake vortex detection techniques developed in the course of European researches.

Huenecke, K.

"THE CHARACTERISATION OF TRANSPORT AIRCRAFT VORTEX WAKES"

AIAA Paper No. 2001-2427, Anaheim, CA, June 2001

Airlines, airports and authorities are searching for advanced solutions of how to accommodate the growing air traffic, without degrading the high standards of safety. One of the most promising routes to improve the capacity situation is to reduce separation distances between aircraft. Separation is necessary, both horizontally for landing and take-off, and vertically for certain enroute legs, to avoid the risk of encountering wakes from preceding aircraft. Hence, separations are vital to assure flight safety. Because the hazard from vortices is growing with aircraft size, the wake vortex issue is becoming even more critical with the appearance of very large transport aircraft (VLTA) from 2005 onward. Standards should be defined which allow a wake to be identified according to certain characteristics. Such characterization parameters conveniently result from experimental evidence and may serve as guidance for prediction methods. The extent of possible characterization parameters reflects the complexity of vortex wakes, and the numerous influencing factors that have to be considered.

Huenecke, K.

"METHOD AND APPARATUS FOR REDUCING TRAILING VORTICES IN THE WAKE OF AN AIRCRAFT"

US Patent 6,513,761 B2, February 2003.

Harmful trailing vortices downstream of an aircraft wing are at least partly dissipated by a respective counteracting vortex for each trailing vortex at each wing. An auxiliary counteracting vortex generating flap, preferably in the form of at least part of a delta wing, is journaled to the respective wing near the outer end of a landing flap. The counteracting vortex is imposed on the respective trailing vortex, whereby the trailing vortex is caused to vibrate. The vibration dissipates the trailing vortex at least partially.

Huenecke, K.

"FROM FORMATION TO DECAY - EXTENDED-TIME WAKE VORTEX CHARACTERISTICS OF TRANSPORT-TYPE AIRCRAFT"

AIAA Paper No. 2002-3265, St. Louis, MO, June 2002

A major impediment to making full use of airspace and airport capacities is a lack of sufficiently understanding fluid dynamics of vortex wakes generated by aircraft. European research efforts have greatly contributed to filling this gap. Findings from experiments were dealt with which were obtained by using near-realistic generic half and full models in wind tunnels and a towing tank. The techniques employed allowed the complete lifetime of a wake to be accessed, from formation to decay. The different behavior of wakes from high-lift and cruise configurations is to be noted. Knowledge from this research may support in establishing methodologies which allow a more realistic description of wake behavior. The towing tank, in combination with advanced measuring and evaluation techniques, was found a useful tool to measure wakes over their complete lifetime.

Huenecke, K.

"VORTEX WAKES FROM LARGE AIRCRAFT - A CHALLENGE FOR INDUSTRIAL RESEARCH"

AIAA Paper No. 2000-2216, Denver, CO, June 2000

Great efforts have been made in recent years to increase the knowledge base on aircraft-generated wakes. Examples given demonstrate the complexity of the wake flow field in the near field where the formation of concentrated vortices takes place. In the light of a new class of high-capacity airliners that will enter service in the next decade, research must greatly intensify to better understand wake physics in particular, so that vortex-related hazards can be quantified and means to hazard reduction can be implemented.

Huenecke, K.

"RECENT DEVELOPMENTS IN INDUSTRIAL WAKE VORTEX RESEARCH"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

The capacity limitation of today's airspace and that of major airports is of increasing concern, especially if air traffic continues to grow at the present rate of 5% per year. One of the most promising routes to increase capacity is to reduce separation distances between aircraft. Separation is necessary, both horizontally for landing and take-off, and vertically for certain enroute legs to avoid the risk of encountering wakes from preceding aircraft. Hence, separations are vital to assure flight safety. Because the hazard from vortices increases with aircraft size, the wake vortex issue is becoming even more critical with the appearance of very-large transport aircraft (VLTA) from 2005 onward. Indeed, 'Wake vortex' is among the major issues that will affect the super airplane of the future, and growth of air traffic in general. Although numerous investigations were carried out worldwide in the past, it was realized that the available database was only of limited value for the industry. Therefore, dedicated research activities, both on a national and supra-national level, were launched by major European nations which focus on the characterization, and then on control, of vortex-dominated wakes.

Huenecke, K.

"WAKE VORTEX INVESTIGATIONS OF TRANSPORT AIRCRAFT"

AIAA Paper No. 1995-1773, San Diego, CA, June 1995

The problem of wake turbulence, because of its hazardous effects on flight safety, continues to be of concern to commercial aviation and aircraft manufacturers alike. Despite considerable research efforts in the past, surprisingly little is still known about wakes trailing behind aircraft. To obtain a more comprehensive understanding of the fundamentals of the formation process, several carefully selected wind tunnel tests were carried out at the DA-Airbus low-speed wind tunnel facility at Bremen, using a

half model with single and double-slotted flaps. Initial results revealed unexpected flow phenomena both in the tip and flap vortices, the knowledge of which may contribute to mitigation of the wake vortex issue.

Huenecke, K.

"STRUCTURE OF A TRANSPORT AIRCRAFT-TYPE NEAR FIELD WAKE"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 5-1 to 5-9

Investigations were carried out using the 2m x 2m low-speed wind tunnel at Bremen. Tests comprised near-field wake flow surveys using a five-hole probe. The results reveal the structure of a near field wake to be of complex nature, even though only the steady-state sector of the flow was accessible with the available testing gear. Flow field evaluation focused on: vortex relative motion, streamwise vortex development, crossflow velocity structure, streamwise velocity structure, total pressure loss, and streamwise vorticity redistribution.

Huenecke, K. and Huenecke, C.

"FLOWFIELD VISUALIZATION IN AIRCRAFT WAKE VORTEX RESEARCH"

Proceedings of 9th International Symposium on Flow Visualization, Edinburgh, Scotland, August 2000, pp. 139-1-139-12

Continuing growth of air traffic has made 'Wake Vortex' one of the most challenging technical issues in modern civil aviation. The requirement for reduced separation distances on densely flown approach routes is closely linked to the hazard caused by wake-generating aircraft and its safety impact on following aircraft. Great efforts have been made in recent years to increase the knowledge base of aircraft-generated wakes. Examples given demonstrate the complexity of the wake flow field in the near field where the formation to concentrated vortices takes place. In the light of a new class of high-capacity airliners to enter service in the next decade, research must even more intensify to better understand wake physics, so that vortex-related hazards can be quantified and means for hazard reduction implemented. A major role to achieve this goal is seen in utilizing modern visualization techniques that became available in recent years. Due to a consequent application of visualization tools, a major insight into vortical flow fields was gained.

Huffaker, R. M.

"SOLID-STATE COHERENT LASER RADAR FOR ATMOSPHERIC SENSING"

Pacific Rim Conference on Lasers and Electro-Optics (CLEO), IEEE, Vol. 2, 1999, pp. 147-148.

Coherent laser radar systems have been developed and applied to atmospheric wind field measurements, aircraft wake vortex monitoring, aerosol plume tracking, airport wind shear and gust front monitoring, as well as military air cargo drops.

Huffaker, R. M.

"LASER DOPPLER SYSTEM FOR AIRCRAFT TRAILING VORTEX TRACKING AND MEASUREMENT"

Proceedings of the Second Annual Research and Technology Review, NASA, October 1974

MSFC has developed a CO₂ Laser Doppler System for the tracking and measurement of aircraft trailing vortices under an interagency agreement between NASA and the FAA. This system has been installed at Kennedy International Airport after checkout at MSFC. This paper describes the logic for the systems design and outlines some of the hardware considerations used in the development. Results of system performance in the tracking and measurement of aircraft trailing vortices will be given.

Huffaker, R. M. and Hannon, S. M.

"AIRPORT SURVEILLANCE USING A SOLID STATE COHERENT LIDAR"

Fifth and Final Combined Manufacturers' and Technologists' Conference, Part 2, Airborne Windshear Detection and Warning Systems, NASA Langley Research Center, VA, July 1994, pp. 499-523

The utility of solid-state coherent LIDAR was assessed in the following application areas; (1) wake vortices; (2) dry and wet microburst windshear; (3) gusts; (4) vertical and general wind profiling; and (5) cloud ceiling. The system performance model described was based on a concept definition, system sizing, measurement planning, and algorithm and graphics display development. Data were collected at the Kennedy Space Center and the National Weather Service site adjacent to Denver's Stapleton Airport.

Huffaker, R. M. and Hardesty, R. M.

"REMOTE SENSING OF ATMOSPHERIC WIND VELOCITIES USING SOLID-STATE AND CO₂ COHERENT LASER SYSTEMS"

IEEE Proceedings, Vol. 84, No. 2, February 1996, pp. 181-204

Coherent lidar/laser radar systems have been used for the remote measurement of atmospheric wind velocity since 1966. Both CW and pulsed coherent lidars have been developed and applied to a variety of ground-based and airborne applications. In recent years, most efforts have concentrated on pulsed carbon dioxide and solid-state Doppler lidars for the remote measurement of atmospheric wind velocities. Issues associated with the design and application of coherent lidars to atmospheric wind measurement are discussed. Coherent lidar/laser radar systems have been applied to detection and tracking of aircraft wake vortices, measurement of atmospheric wind fields during the space shuttle

takeoff and landing, airborne windshear detection, ground-based airport microburst windshear monitoring, meteorological research, and environmental monitoring. Numerous examples of measurement results are presented. An assessment of the status of coherent lidar technology as practical devices for operational and research uses is addressed.

Huffaker, R. M. and Reveley, P. A.

"SOLID-STATE COHERENT LASER RADAR WIND FIELD MEASUREMENT SYSTEMS"

Proceedings of the Lidar Atmospheric Monitoring Meeting, Munich, Germany, June 16-18, 1997, Society of Photo-Optical Instrumentation Engineers (SPIE) Proceedings, Vol. 3104, 1997, pp. 179-189.

Diode-pumped solid-state pulsed coherent laser radar systems have recently been developed for the remote measurement of atmospheric wind fields. Flash-lamp pumped systems have been utilized since 1990 for obtaining wind field measurements. These flash-lamp pumped lidar systems have been applied to wind profiling, aircraft wake vortex measurements, airport wind shear and gust from monitoring, and military cargo air drops and many other applications. The diode-pumped coherent lidar systems currently available are capable of near-turnkey operation. The Tm:YAG laser transceivers operate at 2.02 microns with output pulse energies of 1 to 10 mJ with PRF's of 1,000 to 100 Hz respectively. Range resolution of 30-75 m is typical. A real-time lidar signal processor has also been developed for collecting and analyzing laser radar (lidar) data. The signal processor is based on a commercial PC architecture and offers a real-time data acquisition, analysis, display, recording, and playback environment. Wind measurements and overall system performance results are presented. Wind measurement performance, for a variety of applications, is presented using flashlamp- and diode-pumped coherent lidars including measured wind profiles from ground and on aircraft, wake vortex tracking results, and example flows over mountain terrain.

Huffaker, R. M. and Reveley, P. A.

"SOLID-STATE COHERENT LASER RADAR WIND FIELD MEASUREMENT SYSTEMS"

Pure Applied Optics, Vol. 7, 1998, pp. 863-873.

Diode-pumped solid-state pulsed coherent laser radar systems have recently been developed at Coherent Technologies, Inc., for the remote measurement of atmospheric wind fields. Flash-lamp pumped systems have been utilized since 1990 for obtaining wind field measurements. These flash-lamp pumped lidar systems have been applied to wind profiling, aircraft wake vortex measurements, airport wind shear and gust from monitoring, and military cargo air drops and many other applications. The diode-pumped coherent lidar systems currently available are capable of near turnkey operation. The Tm:YAG laser transceivers operate at 2.02 microns with output pulse energies of 1 to 10 mJ with PRFs of 1000 to 100 Hz, respectively. Range resolution of 30-75 m is typical. A real-time lidar signal processor has also been developed for collecting and analyzing laser radar (lidar) data. The signal processor is based on a commercial PC architecture and offers a real-time data acquisition, analysis, display, recording, and playback environment. Wind measurements and overall system performance

results will be presented. Wind measurement performance, for a variety of applications, is presented using the flashlamp- and diode-pumped coherent lidars including measured wind profiles from ground and on aircraft, wake vortex tracking results, and example flows over mountain terrain.

Huffaker, R. M., Jeffreys, H. B., Weaver, E. A., Bilbro, J. W., Craig, G. D., George, R. W., Gleason, E. H., Marrero, P. J., Reinbolt, E. J. and Shirey, J. E.

"DEVELOPMENT OF A LASER DOPPLER SYSTEM FOR THE DETECTION, TRACKING, AND MEASUREMENT OF AIRCRAFT TRAILING VORTICES"

FAA-RD-74-213, March 1975, NASA Marshall Space Flight Center, Huntsville, AL.

A Scanning Laser Doppler Vortex System (SLDVS) has been developed for use as an aircraft trailing vortex detection, tracking, and measuring system. The report describes the SLDVS design, development, and checkout at NASA. Previous efforts had demonstrated the capability of laser Doppler systems to accurately measure remote wind velocity and turbulence. To assure the proper overall system design; tradeoff studies were performed to determine the optimum design parameters that met the program objectives. Computer simulations of the SLDVS performance were used in determining the optimum design parameters. The SLDVS scans both in range and angle. A real-time vortex display system is provided which gives the vortices' center positions in the scan plane as a function of time. The SLDVS was integrated and checked out at MSFC. The SLDVS has demonstrated overall systems accuracy against known calibrated targets of + 3.3 ft at 492 ft (+ 1 m at 150 m). During cooperative flybys at MSFC, the SLDVS has located the center positions of the B-737 and B-720 aircraft vortices to within + 10 ft (+ 3 m).

Huffaker, R. M., Jelalian, A. V. and Thomson, J. A. L.

"LASER-DOPPLER SYSTEM FOR DETECTION OF AIRCRAFT TRAILING VORTICES"

IEEE Proceedings, Vol. 58, No. 3, March 1970, pp. 322-326

The paper reviews the results of a test program utilizing a CW CO₂ laser-Doppler velocimeter system that has demonstrated the capability of detecting wing tip vortices by the measurement of Doppler shifted back scatter from atmospheric aerosols naturally suspended in the atmosphere. The velocity signatures of vortices generated by a C-47 aircraft making low altitude cooperative flybys are shown. Some considerations of an operational detection system are given.

Huffaker, R. M., Jelalian, A. V., Keene, W. H. and Sonnenschein, C. M.

"APPLICATION OF LASER DOPPLER SYSTEMS TO VORTEX MEASUREMENT AND DETECTION"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 113-124

A laser Doppler system for the measurement of atmospheric wind velocity and turbulence has been developed. This system utilizes the Doppler frequency shift undergone by a beam of radiation when

scattered by particles suspended in the flows. A three-dimensional system has been developed for wind tunnel and jet type flow studies; measurements of velocity have been made for velocities in excess of Mach 2 and compared with theory and hot wire instrumentation. The laser Doppler system has also been applied to the problem of detecting the presence of an aircraft trailing vortex. The results showed that when the vortex was visually sighted and known to be in the sensitive scattering volume of the laser Doppler system, the velocity distribution of the vortex was measured.

Huhnd, M. and Schmid-Goller, S.

"ASPECTS OF LOW SPEED WIND TUNNEL TESTING ON AN A400M MODEL WITH PROPELLER SIMULATION"

In New Results in Numerical and Experimental Fluid Mechanics III, Notes on Numerical Fluid Mechanics, Vol. 77, Eds. Wagner, et al., Springer-Verlag, Berlin Heidelberg, 2002, pp. 82-91.

A400M is the future European military airlifter which is currently developed to fulfil the requirements of eight European Nations. The aircraft will be driven by four turboprop engines. The disc loading of the propellers is significantly higher than realized on former tactical transport aircraft like C130H or Transall C160. Due to the tactical and logistic tasks of this airplane the high and low speed propeller interference effects contribute essentially to the A/C sizing and configuration development. The following presentation deals with aspects of wind tunnel testing with propulsion simulation in the EADS Low Speed Wind Tunnel in Bremen. The simulation of realistic propeller effects is described. Investigations on an isolated propeller are illustrated and the main results of the test campaigns, focusing on propeller effects at high lift configuration are presented.

Hull, J., Barmore, B. and Telence, A.

"TECHNOLOGY-ENABLED AIRBORNE SPACING AND MERGING"

23rd Digital Avionics Systems Conference, Salt Lake City, UT, October 2004

Over the last several decades, advances in airborne and groundside technologies have allowed the Air Traffic Service Provider (ATSP) to give safer and more efficient service, reduce workload and frequency congestion, and help accommodate a critically escalating traffic volume. These new technologies have included advanced radar displays, and data and communication automation to name a few. In step with such advances, NASA Langley is developing a precision spacing concept designed to increase runway throughput by enabling the flight crews to manage their inter-arrival spacing from TRACON entry to the runway threshold. Precision spacing is enabled by Automatic Dependent Surveillance-Broadcast (ADS-B), which provides air-to-air data exchange including position and velocity reports; real-time wind information and other necessary data. On the flight deck, a research prototype system called Airborne Merging and Spacing for Terminal Arrivals (AMSTAR) processes this information and provides speed guidance to the flight crew to achieve the desired inter-arrival spacing. AMSTAR is designed to support current ATC operations, provide operationally acceptable system-wide increases in approach spacing performance and increase runway throughput through system stability, predictability

and precision spacing. In addition to providing for precision inter-arrival spacing, AMSTAR provides speed guidance for aircraft on converging routes to safely and smoothly merge onto a common approach. Much consideration has been given to working with operational conditions such as imperfect ADS-B data, wind prediction errors, changing winds, differing aircraft types and wake vortex separation requirements.

Hummel, D.

"ON THE VORTEX FORMATION OVER A SLENDER WING AT LARGE ANGLES OF INCIDENCE"

High Angle of Attack Aerodynamics, AGARD CP-247, 1978, pp. 13-1 - 13-17.

An experimental study of the flow field around an A=1 delta wing at an angle of attack of 20.5 degrees is presented. The free vortex sheets generated at the wing leading edges roll up into the well-known leading-edge vortices which are accompanied by some secondary vortices at the wing surface because of boundary-layer separations. The effect of Reynolds number on the formation of the secondary vortex is studied in detail. Boundary-layer measurements have been carried out for laminar and turbulent boundary layers and the bound vortex lines in the lifting surface have been determined for both cases. The free vortex sheet originating from the wing trailing edge rolls up into a concentrated trailing vortex the rotation of which is opposite to that of the leading-edge vortex. The flow field has been measured in four planes perpendicular to the free stream direction and located in different positions downstream of the wing trailing edge. The magnitude and the direction of the local velocity vector have been determined by means of a 5-hole probe. The results are given for each plane by lines of constant total pressure, static pressure, dynamic pressure and by a presentation of the local flow directions. The interference between leading-edge vortex, secondary vortex and trailing-edge vortex is studied in detail. The positions of the vortex sheets and of all concentrated vortices in relation to the wing are given quantitatively. They are now available for comparisons with results of numerical calculations.

Hummel, D.

"THE USE OF AIRCRAFT WAKES TO ACHIEVE POWER REDUCTIONS IN FORMATION FLIGHT"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 36-1 to 36-13

Many migrating bird species fly in regular V-shaped formations. Each wing experiences an upwash field generated by all other wings in the formation and this leads to a reduction in flight power demand for each wing as well as for the whole formation. In this paper the aerodynamic interference is studied by means of aerodynamic theory. The total energy saving for the whole formation increases with the number of wings and with decreasing lateral distance. Local power reductions are highest in the inner parts of a formation and they decrease towards the apex and the side-edges. The technical realization of this principle is analyzed for two airplanes. In calibration flights of gliders large distances must be kept or the aerodynamic interference must be considered. In formation flights of two airplanes a

power reduction of 15% is obtainable for the rear airplane flying close to the wake of the front aircraft. The corresponding aileron and rudder deflections for compensation of the corresponding moments are small. Flight tests with two airplanes DO-28 show that the power reduction can be achieved in practical flight. The results are in excellent agreement with aerodynamic theory. To enable the rear airplane to find the proper position relative to the wake of the front airplane an automatic control system has been adapted. A formation flight controller has been designed which leads the upwash in the symmetry plane and the aileron deflections to maximum values. The application of this control system led to a considerable relief of the pilot and important power reductions could be achieved automatically.

Hunecke, K.

"WAKE VORTEX CONTROL - A CHALLENGE FOR LARGE TRANSPORT AIRCRAFT"

Air and Space Europe, Vol. 3, Issues 3-4, May-August 2001, pp. 209-213.

One of the many promising routes to increase capacity at over-crowded European airports is to reduce the separation distance between aircraft on landing and take-off, or vertical separations in densely flown enroute sectors. Separations are necessary to avoid the risk of encountering a wake from a preceding aircraft - and hence are vital for flight safety. This is becoming even more critical with the advent of very-large transport aircraft. This article explains the characterization of wave vortices, and explores the European Projects looking at the problem.

Hunt, D. L., Cummings, R. M. and Giles, M. B.

"WAKE INTEGRATION FOR THREE-DIMENSIONAL FLOWFIELD COMPUTATIONS: APPLICATIONS"

Journal of Aircraft, Vol. 2, March-April 1999, pp. 366-373.

A momentum balance approach is used to extract lift and drag from flow field computations for wings and wing/bodies in subsonic/transonic flight. The drag is decomposed into vorticity, entropy, and enthalpy components that can be related to the established engineering concepts of induced drag, wave and profile drag, and engine power and efficiency. This decomposition of the drag is useful in formulating techniques for accurately evaluating drag using computational fluid dynamics calculations or experimental data. A formulation for reducing the size of the region of the crossflow plane required for calculating the forces is developed using cutoff parameters for viscosity and entropy. This improves the accuracy of the calculations and decreases the computation time required to obtain the results. The improved method is applied to a variety of configurations, including an elliptic wing, the M6 wing, the W4 wing-body, the M165 wing-body fore plane, and the Lockheed Wing A. The accuracy of the force calculations is related to various aspects, including the axial position of the downstream crossflow plane, grid type (structured or unstructured), grid density, flow region (subsonic or transonic), and boundary conditions.

Hunt, J. C. R., Delfos, R., Eames, I. and Perkins, R. J.

"VORTICES, COMPLEX FLOWS AND INERTIAL PARTICLES"

Journal of Flow, Turbulence and Combustion, Vol. 79, 2007, pp. 207-234.

The properties of vortical structures at high Reynolds number in uniform flows and near rigid boundaries are reviewed. New properties are derived by analyzing the dynamics of the main flow features and the related integral constraints, including the relations between mean swirl and bulk speed, the relative level of internal fluctuations to bulk properties, and connections between the steadiness and topology of the structures. A crucial property that determines energy dissipation and the transport of inertial particles (with finite fall speed) is the variation across the structure of the ratio of the mean strain rate to the mean vorticity. It is shown how, once such particles are entrained into the vortical regions of a coherent structure, they can be transported over significant distances even as the vortices grow and their internal structure is distorted by internal turbulence, swirling motions and the presence of rigid boundaries. However, if the vortex is strongly distorted by a straining motion so that the mean strain rate is greater than the mean vorticity, the entrained particles are ejected quite rapidly. These mechanisms are consistent with previous studies of entrained and sedimented particles in disperse two phase flows over flat surfaces, and over bluff obstacles and dunes. They are also tested in more detail here through laboratory observations and measurements of 50-200-micron particles entrained into circular and non-circular vortices moving first into still air and then onto rigid surfaces placed parallel and perpendicular to the direction of motion of the vortices.

Huntley, S. J., Jones, D. and Gaitonde, A.

"WINGTIP VORTEX PRESERVATION USING A COUPLED VORTEX PARTICLE METHOD AND COMPUTATIONAL FLUID DYNAMICS SOLVER"

AIAA Paper 2017-4405, June 2017, Denver, CO.

This paper presents a coupled Vortex Particle Method-Computational Fluid Dynamics solver. The Vortex Particle Method solution is used to correct the Computational Fluid Dynamics. This is achieved by using the Split Velocity Method, which includes the influence of the particles through their induced velocities and additional source terms. The coupled solver is demonstrated on a two-dimensional and three-dimensional test case and the results are compared to the solutions of the CFD solver on its own using a coarse mesh and a fine mesh. It is shown that the hybrid solver preserves the tip vortex on a coarse mesh and is computationally more efficient than using the fine mesh.

Huppertz, G., Fares, E., Abstiens, R. and Schroder, W.

"INVESTIGATION OF ENGINE JET/WING-TIP VORTEX INTERFERENCE"

Aerospace Science and Tech., Vol. 8, 2004, pp. 175-183

The wing-tip vortex of a rectangular wing half-model with a model engine is studied experimentally and numerically. The airfoil has a supercritical BAC 3-11/RES/30/21 geometry with a chord length of $c =$

150 mm. The investigations include three different spanwise positions of the engine and two jet velocities with a constant free stream velocity. The numerical simulation is divided into two parts. First the flow around the airfoil is calculated. In a second step the data is taken as an input to calculate the wake downstream of the trailing edge. Experiments include 2C- and 3C-PIV-measurements for the velocity distribution of the jet and the wing-tip vortices. The experimental and numerical results show the significance of the streamwise velocity component for the analysis of the jet/wing-tip vortex interaction.

Huppertz, G., Klaas, M. and Schroeder, W.

"PIV MEASUREMENTS OF UNSTEADY VORTEX BEHAVIOR IN THE NEAR WAKE OF A SWEPT WING MODEL"

13th International Symposium on Application of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, June 2006

The results indicate that a span wise change of the location of the engine jet modifies the stability properties of the wake flow. Depending on the engine position, the operation mode, and the wing configuration, the unsteady vortex behavior and the vortex topology are different and the interaction of wing tip and flap edge vortices is affected.

Huppertz, G., Schroder, W. and Klaas, M.

"ENGINE JET/VORTEX INTERACTION IN THE NEAR WAKE OF AN AIRFOIL"

AIAA Paper 2006-3747, June 2006, San Francisco, CA

Experimental results concerning the engine jet/vortex wake interaction will be presented. A method is described that improves the evaluation of unsteady vortex measurements and allows to analyze the effect of unsteady vortex movement. The results indicate that the engine jet modifies the stability properties of the wake flow. Depending on the engine position and operation mode the mean wandering amplitudes and the velocity fluctuations in the vortex wake are different and the topology of the vortex is affected. The current results suggest that for high-lift configurations the preferable engine position is closer to the wingtip if the focus is on the stability properties of the vortex wake.

Huppertz, G., Schroder, W. and Klass, M.

"ENGINE JET/VORTEX INTERACTION IN THE NEAR WAKE OF AN AIRFOIL"

AIAA Paper No. 2006-3747, San Francisco, CA, June 2006

Experimental results concerning the engine jet/vortex wake interaction will be presented. A method is described that improves the evaluation of unsteady vortex measurements and allows to analyze the effect of unsteady vortex movement. The results indicate that the engine jet modifies the stability properties of the wake flow. Depending on the engine position and operation mode the mean

wandering amplitudes and the velocity fluctuations in the vortex wake are different and the topology of the vortex is affected. The current results suggest that for high-lift configurations the preferable engine position is closer to the wing-tip if the focus is on the stability properties of the vortex wake.

Hure, N. and Borrel, M.

"A MULTIBLOCK MULTIGRID AMR METHOD IN 3D USING A MUSCL OR A DISCONTINUOUS GALERKIN APPROACH"

3rd International Symposium on Finite Volumes for Complex Applications, June 24-28, 2002, Porquerolles, France

In this paper we present a 3D implementation of the AMR method for curvilinear or Cartesian grids. Two compressible flow solvers (MUSCL and DG) are used. The adapted solutions of the transonic flow past a twisted wing and of the wake vortex of a A300 model show the capabilities of this method.

Husain, H. S., Shtern, V. and Hussain, F.

"CONTROL OF VORTEX BREAKDOWN BY ADDITION OF NEAR-AXIS SWIRL"

Physics of Fluids, Vol. 15, No. 2, February 2003, pp. 271-279

We present a new method for controlling vortex breakdown (VB) via addition of co- or counter-rotation near the axis. Co-rotation is adequate to totally suppress VB, whereas counter-rotation increases the number and size of VB 'bubbles' and makes the flow unsteady. We study these effects in a closed cylindrical container, in which a rotating end disc drives the base flow; an independently rotating central rod (with rod radius much less than disk radius) is employed to control VB. This flow, being free of ambient disturbances, is well suited for understanding both the VB mechanism and its control; the present work appears to be the first to study VB control. We develop and explain our control strategy using flow visualization and simple analytical reasoning. Our results suggest that an additional co- or counter-rotation, applied near the vortex axis, can be effective in suppressing or enhancing VB in practical flows.

Hussain, F.

"DYNAMICS OF SLENDER VORTICES NEAR THE WALL IN A TURBULENT BOUNDARY LAYER"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

It is now well-established that the enhanced drag and heat transfer of turbulent boundary layers is dominated by slender longitudinal vortices immediately near the wall. Despite their immense practical significance, the geometry and dynamics of near-wall vortices are not well understood and often controversial. To gain new insight into the near-wall dynamics, we deduce coherent structures (CS) near the wall from a numerically simulated turbulent channel flow using a conditional sampling scheme which extracts the entire extent of locally dominant vortical structures. Such structures are detected

from the instantaneous flow field using our newly developed vortex definition -- a region of negative λ_2 , the second largest eigenvalue of the tensor $S_{ik}S_{kj} + \Omega_{ik}\Omega_{kj}$ -- which accurately captures the structure details, unlike velocity, vorticity or pressure-based reduction schemes. Extensive testing shows that λ_2 correctly captures vortical structures, even in the presence of strong shear occurring near the wall of a boundary layer. Our conceptual model of the CS array reproduces nearly all experimentally observed events reported in the literature, such as VITA, gradient and counter-gradient Reynolds stress distributions (Q1, Q2, Q3 and Q4 and their relative contributions), wall pressure variation, elongated low-speed streaks, spanwise shear, etc. Notably, the often-heralded hairpin vortices, not to be confused with hairpin-shaped vortex line bundles, are absent both in the instantaneous and ensemble-averaged fields. We have also discovered a new instability mechanism for generation of these dominant longitudinal vortices from a basic flow initially containing no streamwise vorticity. The structure evolution agrees quite well with that observed in DNS of minimal channel flow.

Hussain, F., Pradeep, D. S. and Stout, E.

"NONLINEAR TRANSIENT GROWTH IN A VORTEX COLUMN"

Journal of Fluid Mechanics, Vol. 682, 2011, pp. 304-331.

Growth of optimal transient perturbations to an Oseen vortex column into the nonlinear regime is studied via direct numerical simulation (DNS) for Reynolds number, Re (circulation/viscosity), up to 10000. An optimal bending-wave transient mode is obtained from linear analysis and used as the initial condition. (DNS of a vortex column embedded in finer-scale turbulence reveals that optimal modes are preferentially excited during vortex-turbulence interaction.) Tilting of the optimal mode's radial vorticity perturbation into the azimuthal direction and its concomitant stretching by the column's strain field produces positive Reynolds stress, hence kinetic energy growth. Modes experiencing the largest growth are those with initial vorticity localized at a 'critical radius' outside the core, such that this perturbation vorticity resonantly induces core waves. Resonant forcing leads to growth of perturbation energy concentrated within the core. Moderate-amplitude (about 5 percent) perturbations cause significant distortion of the core and generate secondary filament-like spiral structures ('threads') outside the core. As the mode evolves into the nonlinear region, radially outward self-advection of thread dipoles accelerates growth arrest by removing the perturbation from the critical radius and disrupting resonant forcing. With increasing Re , the evolving vorticity patterns become more chaotic, more turbulent-like (finer scaled, contorted vorticity), and persist longer. This suggests that at typical Re (about 1,000,000), nonlinear transient growth may indeed be able to break up, hence induce rapid decay of, column vortices -- highly relevant for addressing the aircraft wake hazard crisis and the looming air traffic capacity crisis. In addition, we discover a regenerative transient growth scenario in which threads induce secondary perturbations closer to the vortex column. A parent-offspring regenerative mechanism is postulated and verified by DNS. There is a clear trend towards stronger regenerative growth with increasing Re . These results, showing an important role of transient growth in turbulent vortex decay, are highly relevant to the prediction and control of vortex-dominated flows.

Hutcheson, F. V. and Stead, D. J.

"PIV MEASUREMENTS ON A BLOWING FLAP"

AIAA Paper No. 2005-0212, Reno, NV, January 2005

PIV measurements of the flow in the region of a flap side edge are presented for several flap configurations. The test model is a NACA 63-215 Hicks Mod-B main-element airfoil with a half-span Fowler flap. Air is blown from small slots located along the flap side edge on either the top, bottom, or side surfaces. The experimental set up is described and flow measurements are presented for a baseline and three blowing flap configurations. The effects that the flap tip jets have on the structure of the flap side edge flow are discussed for each of the flap configurations tested. The results indicate that blowing air from a slot located along the top surface of the flap greatly weakened the top vortex system and pushed it further off the top surface. Blowing from the bottom flap surface kept the strong side vortex further outboard while blowing from the side surface only strengthened the vortex system or accelerated the merging of the side vortex to the flap top surface. It is concluded that blowing from the top or bottom surfaces of the flap may lead to a reduction of flap side edge noise.

Hwang, J. Y., Choi, J. H. and Kwon, O. J.

"ASSESSMENT OF S-76 ROTOR HOVER PERFORMANCE IN GROUND EFFECT USING AN UNSTRUCTURED MIXED MESH METHOD"

AIAA Paper 2016-0033, January 2016, San Diego, CA.

In the present study, the aerodynamic performance of an S-76 rotor in hover was numerically investigated by using an unstructured mixed mesh flow solver. The study was made for the rotor for both OGE (out-of-ground-effect) and IGE (in-ground-effect) conditions, and the results are compared against each other. In the present mixed mesh methodology, body-fitted prismatic/tetrahedral mesh was adopted in the near-body flow domain to easily treat complex geometries and to capture the viscous layer on the solid surface accurately, while in the off-body region away from the blades Cartesian mesh was used. To better resolve the flow characteristics and to prevent numerical dissipation, high-order accurate weighted essentially non-oscillatory (WENO) scheme was employed in the off-body flow region. An overset mesh technique was adopted to treat the rotating blades and to exchange the flow variables between the two different mesh regions. The calculations were made for three different blade configurations, having swept-tapered, rectangular, and swept-tapered-anhedral tip shapes, and the results are compared with experimental rotor performance data in terms of thrust, torque and figure of merit. The predictions were obtained for a collective pitch angle sweep from 5 to 10 degrees at a tip Mach number of 0.60 for both cases with and without ground effect. The detailed flow characteristics, such as the vorticity contours and the tip-vortex trajectory, were also investigated.

Iafrati, A. and Riccardi, G.

"A NUMERICAL EVALUATION OF VISCOUS EFFECTS ON VORTEX INDUCED NOISE"

Journal of Sound and Vibration, Vol. 196, Issue 2, September 1996, pp. 129-146

The effect of viscosity on the noise generated by interactions of simple axisymmetric vorticity structures is numerically investigated. A low Mach number is assumed, and hence the feedback of the acoustic field on the flow can be neglected. With this assumption, Lighthill's acoustic analogy enables one to determine the far field pressure perturbation due to vorticity motion. For a swirl-free incompressible flow, numerical simulations are performed with a finite difference scheme in terms of the vorticity and the stream function. The acoustics of collision and pairing of vortex rings is investigated for growing Reynolds numbers. Results show that the quadrupole term converges to the inviscid one, while the acoustic term due to the energy dissipation vanishes, according to the theoretical prediction of Obermeier.

Iannotta, B.

"VORTEX DRAWS FLIGHT RESEARCH FORWARD"

Aerospace America, Vol. 40, No. 3, March 2002, pp. 26-30

Following a lead aircraft at just the right location in its vortex may prove a feasible way to fly farther and save fuel.

Iannuzzelli, R. J., Schemm, C. E., Marcotte, F. J., Manzi, L. P., Gilreath, H. E., Hanson, Jr., J. M., Frostbutter, D. A., Hughes, A. S., Bric, A. D. and Kershner, D. L.

"AIRCRAFT WAKE DETECTION USING BISTATIC RADAR - ANALYSIS OF EXPERIMENTAL RESULTS"

Johns Hopkins APL Technical Digest, Vol. 19, No. 3, July-September 1998, pp. 299-314

The Applied Physics Laboratory has built and fielded an experimental bistatic X-band CW radar system for studies in aircraft wake vortex detection. The radar, along with an acoustic pumping system, was installed at the Baltimore-Washington International Airport in the fall of 1996. Controlled experiments using a NASA C-130 aircraft were conducted on 23 September, 29 October, and 10 December. Results from two specific runs on 29 October are presented and discussed along with numerical simulations of those runs.

Ibrahim, K.

"SELECTING WING LOADING AND THRUST TO WEIGHT RATIO FOR MILITARY JET TRAINERS"

AIAA Paper 2002-3153, June 2002, St. Louis, MO.

Configuration and performance data of jet trainers and light attack airplanes has been analyzed. Correlations have been evolved for selecting wing loading and thrust to weight ratio for baseline design configuration of military jet trainers and light attack airplanes for compliance with a set of mission requirements in terms of 1) take-off distance, b) maximum rate of climb at sea level, c) maximum level speed at any altitude below tropopause, and d) landing distance.

ICAO Journal, Vol. 56, No. 7, September 2001, pp. 8-10, 28.

"Current aircraft separation requirements are effective in preventing wake vortex encounters, but are often overly conservative. Scientists are studying vortex behavior in all weather conditions to determine whether separation requirements may be relaxed under certain conditions."

Ickes, J., Wang, J., Zhao, Q. and Sheng, C.

"COUPLED CFD/CSD SIMULATIONS OF HELICOPTER ROTORS WITH A FREE WAKE MODEL"

AIAA Paper 2014-1251, January 2014, National Harbor, MD.

A Computational Fluid Dynamics/Computational Structural Dynamics (CFD/CSD) coupling technique is used to analyze the four-bladed UH-60A and Bell 427 main rotors, and the results are compared to flight test data. The unstructured Reynolds-Averaged Navier Stokes (RANS) solver U2NCLE was coupled to DYMORE 2 by means of an automated script. A single blade was rendered in the CFD model for each case, and the wake of a four-bladed system was represented by a free wake model. The UH-60A loose coupling flight conditions were the forward flight high speed and moderate speed cases corresponding to flight counters c8534 and c8513, respectively. The Bell 427 flight case simulated was a high-speed forward flight case. After convergence of the coupling procedure air load prediction was improved, and some flow features missed by the low fidelity aerodynamics of the CSD code were resolved by the high-fidelity flow solver. Aerodynamic loads associated with reverse flow and Blade-Vortex Interaction (BVI) showed the most improvement. Blade structural loads predicted by DYMORE 2 showed signs of moderate improvement because of the increased accuracy of the CFD-based air loads for one flight condition.

Igarashi, H., Durbin, P. A., Hu, H., Waltermire, S. and Wehrmeyer, J.

"THE EFFECTS OF WIND TUNNEL WALLS ON THE NEAR-FIELD BEHAVIOR OF A WINGTIP VORTEX"

AIAA Paper No. 2011-1165, January 2011, Orlando, FL.

An experimental study was conducted to investigate the behavior of the wing-tip vortex structures generated by a square-tipped, rectangular NACA0012 wing. A Stereoscopic Particle Image Velocimetry (SPIV) system was used to conduct detailed flow field measurements to elucidate the key features of the wing-tip vortex structure in the near field. One of the great advantages of the present SPIV measurements over the classical measurement technique is that the vortex wandering can be removed directly by tracking the center of the wingtip vortex in the instantaneous measurement frames. By tracking the center of the wingtip vortex, the wandering and turbulence in the vortex can be decoupled completely. This method was applied to investigate the effects of the angle of attack of the test wing and wind tunnel wall on the evolution of the wingtip vortex in the near field. To decouple the effects of vortex wandering, Devenport et al. (1996) suggested an analytical method to predict the wandering free velocity profile. The velocity profile predicted by the Devenport et al. (1996) method was compared with the SPIV re-centered velocity profile quantitatively.

Igarashi, H., Durbin, P. A., Ma, H. and Hu, H.

"A STEREOSCOPIC PIV STUDY OF A NEAR-FIELD WINGTIP VORTEX"

AIAA Paper 2010-1029, January 2010, Orlando, FL.

An experimental study was conducted to investigate the wing-tip vortex generated from a rectangular NACA0012 airfoil model. A high-resolution Stereoscopic Particle Image Velocimetry (SPIV) system was used to conduct detailed flow field measurements to quantify the transient behavior of the wing-tip vortex in the near field. The characteristics of the vortex wandering phenomena, i.e., the slow side-to-side movement of the wing-tip vortex core were revealed in detail based on the SPIV measurement results.

Ignatkin, Iu. M., Makeev, P. V., Shomov, A. I. and Ivchin, V. A.

"COMPUTATIONAL STUDY OF AERODYNAMIC CHARACTERISTICS OF SINGLE-ROTOR HELICOPTER TAIL ROTOR UNDER THE INFLUENCE OF VORTICAL WAKE OF MAIN ROTOR AT THE HOVER WITH CROSSWIND"

Civil Aviation High Technologies, Vol. 19, No. 6, 2016, pp. 58-67.

For single-rotor helicopters there are special flight modes, when tail rotor (TR) is under significant inductive influence of vortical wake of main rotor (MR). Inductive influence of vortical wake of MR can provoke essential changes in flowing of TR and its aerodynamic characteristics compared to isolated rotor. In this case increase of tail rotor pitch, necessary for helicopter controlling, is possible. The article contains computational modelling of TR work with vortical wake of MR at the example of MIL Mi-171 helicopter. The modelling has been made on the basis of non-linear blade (free wake) vortical model of rotor, produced at Helicopter Design Department of MAI. Helicopter hovering modes with crosswind of various intensity V_z were considered. Thrust-time relationship for isolated TR and TR with vortical wake of MR for equal flight modes was obtained. Flow around the rotors was analyzed, the vortical wake was considered. The results make it possible to clarify the peculiarities of TR work on considered modes and MR influence on its work. It was found out that vortical wake of MR has a more significant impact on TR work with crosswind on the right, when TR falls into vortex ring state mode. Inductive influence of vortical wake of TR leads to vortex ring state mode for TR at lower speeds ($V_z \sim 5$ m/s) than in case of isolated work of TR ($V_z \sim 12.5$ m/s). In that case the required tail rotor pitch has increased by 13% for $V_z \sim 5$ m/s. The results of modelling and flight tests led to good agreement. [In Russian.]

Iida, O., Tsujimura, S. and Nagano, Y.

"DIRECT NUMERICAL SIMULATION OF HOMOGENEOUS STRATIFIED ROTATING TURBULENCE"

Theoretical and Computational Fluid Dynamics, Vol. 19, No. 6, 2005, pp. 441-460

The effects of the Prandtl number on stratified rotating turbulence have been studied in homogeneous turbulence by using direct numerical simulations and a rapid distortion theory. Fluctuations under strong stable-density stratification can be theoretically divided into the WAVE and the potential vorticity (PV) modes. In low-Prandtl-number fluids, the WAVE mode deteriorates, while the PV mode remains. Imposing rotation on a low-Prandtl-number fluid makes turbulence two-dimensional as well as geostrophic; it is found from the instantaneous turbulent structure that the vortices merge to form a few vertically-elongated vortex columns. During the period toward two-dimensionalization, the vertical vortices become asymmetric in the sense of rotation.

Ilea, C. G., Kosinski, P. and Hoffmann, A. C.

"NUMERICAL STUDY ON THE DYNAMICS OF A JET-VORTEX INTERACTION"

Applied Mathematics and Computation, Vol. 217, 2011, pp. 5103-5112.

The interaction of a vortex and a jet plays an important role for many industrial processes such as carbon black formation or combustion in diesel engines. The knowledge of physics of these phenomena is crucial for engineers, but also for scientists who wish to study this complex flow pattern. In this research, we numerically investigate cases where a cylindrical reactor is charged with gas injected through five ports. The first one is located along the main axis of the cylinder and this leads to the formation of the main jet. The other four ports are situated along the side walls such that the gas entering the cylinder tangentially through them causes a vortex to be formed. The objective of this paper is to show the fundamental physical phenomena, and also how the initial and boundary conditions influence the results. It is shown how the process is influenced not only by modifying the velocity of injected gas, but also by the orientation and position of the vortex inlet nozzles.

Ilie, M., Nitzsche, F. and Matida, E.

"INFLUENCE OF ANGLE OF ATTACK ON THE HELICOPTER BLADE-VORTEX MECHANISM OF INTERACTION USING LARGE EDDY SIMULATION"

AIAA Paper No. 2008-551, Reno, NV, January 2008

The influence of angle of attack on the helicopter blade-vortex mechanism of interaction is investigated using large eddy simulation (LES). The LES technique provides a promising tool for obtaining the unsteady wall-pressure fields, aerodynamic coefficients, and the acoustic source functions. A large eddy simulation is carried out for parametric investigations of Blade-Vortex Interaction (BVI) problem, for a chord-based Reynolds number of $1.3 \times 1,000,000$. Computations are carried out to investigate the influence of angle of attack on the aerodynamic coefficients.

Ilyin, G. N., Troitsky, A. V., Miller, E. A. and Ganshin, E. V.

"RESULTS OF FIELD EXPERIMENT COMPARISONS OF NEW SELF-CALIBRATED, UNMANNED, GROUND-BASED, MULTICHANNEL RADIOMETER FOR WATER VAPOR AND TEMPERATURE PROFILES MEASUREMENTS"

WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation, September 2016, Madrid, Spain.

Well known problem of multichannel radiometers measurements of water vapor and temperature profiles techniques is the problem of manual calibration procedures. To solve this problem in IAA RAS it was developed self-calibrated and unmanned dual-channel microwave complex WVR-2 (20 and 35 GHz) which measures integrated water vapor and liquid water content in atmosphere. This complex has been combined with single-channel microwave radiometer, with working frequency of 56.6 GHz for continuous measurement of ABL temperature profiles. As result we have received self-clearing, self-calibrated, unmanned and no consumables multichannel radiometer for water vapor, liquid water content and temperature profiles measurements (MRWT). To test stability and accuracy of MRWT it was installed in Central Aerological Observatory, Dolgoprudny, Russia (coordinates 55 deg 55'28.70"N, 37 deg 31'25.55"E) in December 2014. The paper shows the results of comparison of MRWT with radio sounding data (WMO station index 27612) and following devices: multichannel microwave complex for temperature profiles integrated water vapor and liquid water content measurement RPG-HARPRO G4 (Germany) and the results of the GNSS signal, GNSS signal processing (troposphere delay) received by the equipment located in Mendeleevo, Moscow region, at the point with coordinates 56 deg 1'17.18"N, 37 deg 12'52.02"E, altitude 257.1 m was also used to compare the MRWT measurement results of integral water vapor content.

Ilyin, S. P.

"INVESTIGATION OF DYNAMICS AND STABILITY OF VORTEX MULTICOMPONENT FLOW IN THE WAKE OF SUPERSONIC AIRCRAFT"

Report ISTC 1477-02, January 2004, Russian Federal Nuclear Center, Nizhni Novgorod Region, Russia.

The goal of the project is to (1) develop measurement procedures for combustion products (CO₂ mainly) present at various distances of the supersonic airliner engine and determine concentration ranges detectable with these procedures; (2) perform computerized predictions and analysis of a set of fundamental physical processes occurred in the viscous core of the trailing vortex generated behind the wing of supersonic civil aircraft. The report describes a pilot facility built around a tunable CO₂ laser and multi-pass cell, provides experimental results on control of the substance typical for the aircraft wake (carbon oxides and nitrogen, ozone, water vapors, etc.). The conditions typical of the supersonic aircraft wake have been simulated. The feasibility of 80-ppb real time measurements of the substances in question has been shown experimentally. Computerized prediction models have been developed. Results of the calculations of the substances in question generation and evolution in turbulent swirl flow have been obtained. A mathematical model and program code simulating numerically two-phase turbulent flow in isolated trailing vortex and initial stage of contrail formation behind supersonic aircraft have been validated.

Ilyin, S. P., Adamenkov, A. A., Asmolov, E. S., Bulkin, Y. N., Vyskubenko, B. A., Deryugin, M. Y., Kolobyenin, Y. V., Kudryashov, E. A., Rusyanov, D. A. and Shustov, A. V.

"TUNABLE CO₂ LASER MEASUREMENTS OF COMPOSITION AND CONCENTRATIONS IN MULTICOMPONENT WAKE BEHIND SUPERSONIC CIVIL AIRCRAFT"

Proceedings SPIE, Vol. 5777, XV International Symposium on Gas Flow, Chemical Lasers, and High-Power Lasers, April 2005, pp. 1019-1022.

The paper describes experimental and theoretical investigations on tunable CO₂-laser-assisted measurements of the composition and concentrations in multicomponent wake behind supersonic civil aircraft. An experimental facility based on a tunable CO₂ laser and multi-pass cell is presented and results of experiments on determination of substances typical for civil aircraft wake (carbon and nitrogen oxides, ozone, water vapor, etc.) are given. The conditions characteristic of the aircraft wake are simulated. A possibility to perform real-time measurements of substances in question at a level of 80 ppb is demonstrated. Calculative models were created and results of calculations of generation and evolution of substances in question in a turbulent twisted flow are reported. A mathematical model and program code were validated for numerical simulations of two-phase turbulent flow in a single trailing vortex in initial stage of contrail generation behind supersonic aircraft.

Ilyina, I. P.

"NUMERICAL SIMULATION OF THE INTERACTION BETWEEN SMALL PARTICLES AND A VORTEX CLUSTER DURING ITS EVOLUTION IN THE FAR VORTEX WAKE"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 389-395

This paper considers the behavior of tracer particles of different size and density in a vortex cluster near the ground surface and the cases of interaction between small particles and a vortex cluster when it evolves in the far wake behind an aircraft. The method developed for computing particles' trajectories enables investigation of particle motion in the velocity field that is not only specified analytically but also obtained numerically. Initial data for computations are taken from the results of full-scale experiments with the vortex wake generated by the heavy aircraft of the Boeing-747 category. Particle entrainment into vortex motion is investigated for different parameters of the particles and vortices and a set of their mutual arrangements.

Ilyina, I. P. and Soudakov, V. G.

"INVESTIGATION OF THE INFLUENCE OF A TURBULENT ATMOSPHERE ON MOTION OF SMALL PARTICLES IN THE VORTEX WAKE BEHIND AN AIRCRAFT"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 396-400

This work deals with the behavior of tracer particles of various sizes and densities in the vortex cluster in the far vortex wake behind an aircraft in a turbulent atmosphere. An assessment has been made of the time during which various particles remain within a vortex with the purpose to work out requirements for sizes and densities of particles to be used for vortex wake visualization.

Imamura, T., Enomoto, S., Kato, H., Yokokawa, Y. and Yamamoto, K.

"NUMERICAL SIMULATION OF NACA0012 WINGTIP FLOW LEADING TO NOISE GENERATION"

AIAA Paper 2005-2854, May 2005, Monterey, CA.

In this study, a flow around a blunt-tipped wing is solved using Reynolds averaged Navier-Stoke (RANS) equations, detached eddy simulation (DES) and large eddy simulation (LES) in order to simulate flap edge flow structure with a simple one-element wing. A rectangular wing with NACA0012 airfoil section is chosen as a model. A preliminary analysis around this configuration using RANS indicated that the flow structures are similar to that of the flap edge, and consequently the noise generation mechanism is expected to be similar as well. The computed results are compared with that of wind tunnel experiments, which were also performed at JAXA for the purpose of CFD validation. The present unsteady computation using LES indicates the existence of two different noise sources, one around the side edge and the other over the upper surface.

Inamdar, A. R., Lele, S. K. and Jacobson, M. Z.

"REDUCED ORDER MODELING OF CONTRAILS: JET INDUCTION AND VORTEX PHASES"

AIAA Paper 2016-3136, June 2016, Washington, DC.

Persistent contrails are formed downstream of aircrafts at ambient conditions where the Schmidt-Appleman criterion is met. Excess water vapor in the ambient condenses on activated soot particles present in the jet exhaust as it gets entrained by the aircraft wake vortices and interacts with the ambient. Contrails are a matter of considerable interest in the context of their contribution to anthropogenic global warming. This paper introduces a reduced order predictive ODE model for the evolution of integrated quantities of interest (QoIs) of contrails in stationary ambient conditions up to vortex linkage. The QoIs such as wake size, downwash, mean particle size and particle survival rate depend on a wide range of parameters such as wingspan, weight, EI sub ice, fuel burn rate, ambient supersaturation w.r.t. ice, stratification, and turbulence intensity. The impact of the competition and interplay between physical processes that depend on all the aforementioned parameters, on the QoIs, is captured by the present model using only 4 non-dimensional (ND) groupings achieving a huge reduction in the order of the problem and consequently the computational cost. The dynamics of the contrail are sufficiently described using bulk conservation of mass and momentum. The microphysics involves bulk energy conservation of the wake.

Inamdar, A. R., Lele, S. K. and Jacobson, M. Z.

"A PROBABILISTIC ICE HABIT MODEL FOR LES OF CONTRAILS"

AIAA Paper 2013-2553, June 2013, San Diego, CA.

This study aims at using a three-dimensional large-eddy simulation (LES) model for quantifying the effects of non-sphericity of ice particles on the dynamics of aircraft condensation trails. A new model to incorporate ice habits is proposed and used with LES calculations for a time horizon of 20 minutes after the aircraft has passed. It is found that ice particle density and ice area are significantly higher for non-spherical than spherical ice particles -- for an ambient RHi of 130 percent, the ice area is about 30 percent higher while almost all initialized particles remain active throughout the time horizon considered. Optical depth is observed to be about 25 percent higher for non-spherical particles than for spherical particles.

Inasawa, A., Mori, F. and Asai, M.

"DETAILED OBSERVATIONS OF INTERACTIONS OF WINGTIP VORTICES IN CLOSE-FORMATION FLIGHT"

Journal of Aircraft, Vol. 49, No. 1, January-February 2012, pp. 206-213.

The interaction of wingtip vortices in close-formation flight of two wings were examined experimentally. Both wings consisting of a NACA 23012 airfoil section and a rectangular planform of an aspect ratio of 5 were set in echelon formation in a wind tunnel. The lift-to-drag ratio increased the most effectively when the two wings were overlapped with each other by 5 percent of the wingspan with zero vertical offset for the present wing configuration. Flow visualizations and particle image velocimetry measurements showed that the trailing vortex of the lead wing collided at a slightly inboard point of the trail wing and was divided into two streamwise vortices in the most effective overlap condition. It was also observed that the tip vortices of the lead and trail wings interacted closely with each other to form a pair of counter-rotating vortices for smaller overlap conditions less than 5 percent with zero vertical offset. For such small overlap cases, circulation of the trailing vortex of the trail wing was reduced markedly by influences of the trailing vortex of the lead wing.

Ineshin, Yu. L. and Sviridenko, Yu. N.

"APPLICATION OF THE SYMMETRICAL-SINGULARITY PANEL METHOD TO CALCULATING THE FLOW OVER AN AIRCRAFT WITH ACCOUNTING FOR THE EFFECT OF ENGINE EXHAUST JETS"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 41-53

The formation of the near wake behind an aircraft in the airport airspace is considered. Low flight velocities of aircraft during takeoffs and landings allow the usage of panel methods to simulate the flow of an ideal incompressible fluid around aircraft configurations with consideration for the effect of engine exhaust jets. Presented in the work are the results of the computer code's verification using a comparison with analytical solutions, computational results based on other computer codes, and experimental data. [In Russian.]

Inokuchi, H., Furuta, M. and Inagaki, T.

"HIGH ALTITUDE TURBULENCE DETECTION USING AN AIRBORNE DOPPLER LIDAR"

ICAS 2014, September 2014, St. Petersburg, Russia.

Air turbulence is a serious problem that affects airline operations. The Japan Aerospace Exploration Agency (JAXA) is developing an airborne Doppler LIDAR (Light Detection and Ranging) for on-board turbulence detection. Flight experiments demonstrated that a high-altitude prototype can measure wind speeds at the more than 9 km range at altitude of 12 km. This paper describes the development of the airborne Doppler LIDAR and presents sample high-altitude flight experiment results.

Inoue, O. and Hattori, Y.

"ACOUSTIC WAVES GENERATED BY COLLISIONS OF TWO VORTEX RINGS"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

Three-dimensional, unsteady, compressible flow fields produced by collisions of two vortex rings are simulated numerically, and the basic natures of the sound generated by the collisions are clarified. The Navier-Stokes equations are solved by a finite difference method. For spatial derivatives, a sixth-order accurate compact Pade scheme is used for time-integration. The non-reflecting boundary conditions (Poinsot and Lele) are imposed. Non-uniform mesh system is applied in this study to save computation time, because a large computational domain is required in order to capture the sounds in far fields. Two different types of a vortex ring are considered, depending on the initial vorticity distribution: Hill's spherical vortex and Gaussian type.

Inoue, O. and Hattori, Y.

"SOUND GENERATION BY SHOCK-VORTEX INTERACTIONS"

J. Fluid Mech., Vol. 380, 1999, pp. 81-116

Two-dimensional, unsteady, compressible flow fields produced by the interactions between a single vortex or a pair of vortices and a shock wave are simulated numerically. The Navier-Stokes equations are solved by a finite difference method. The sixth-order-accurate compact Pade scheme is used for spatial derivatives, together with the fourth-order-accurate Runge-Kutta scheme for time integration. The detailed mechanics of the flow fields at an early stage of the interactions and the basic nature of the near-field sound generated by the interactions are studied. The results for both a single vortex and a pair of vortices suggest that the generation and the nature of sounds are closely related to the generation of reflected shock waves. The flow field differs significantly when the pair of vortices moves in the same direction as the shock wave than when opposite to it.

Inoue, O., Hattori, Y. and Sasaki, T.

"SOUND GENERATION BY COAXIAL COLLISION OF TWO VORTEX RINGS"

Journal of Fluid Mechanics, Vol. 424, 2000, pp. 327-365.

Sound pressure fields generated by coaxial collisions of two vortex rings with equal/unequal strengths are simulated numerically. The axisymmetric, unsteady, compressible Navier-Stokes equations are solved by a finite difference method, not only for a near field but also for a far field. The sixth-order-accurate compact Pade scheme is used for spatial derivatives, together with the fourth-order-accurate Runge-Kutta scheme for time integration. The results show that the generation of sound is closely related to the change of direction of the vortex ring motion induced by the mutual interaction of the two vortex rings. For the case of equal strength (head-on collision), the change of direction is associated with stretching of the vortex rings. Generated sound waves consist of compression parts and rarefaction parts, and have a quadrupolar nature. For the case of unequal strengths, the two vortex rings pass through each other; the weaker vortex ring moves outside the stronger vortex ring which shows a loop motion. The number of generated waves depends on the relative strength of the two vortex rings. The sound pressure includes dipolar and octa-polar components, in addition to monopolar and quadrupolar components which are observed for the case of a head-on collision.

Isambert, E.

"THE CREDOS PROJECT: COMMUNICATION PLAN"

D5-2, June 2007.

This document describes the approach chosen by the CREDOS project to define the CREDOS communication strategy and then proposes a plan to allow effective and efficient communication towards CREDOS stakeholders and other target audiences throughout the lifecycle of the project (2006-2009). The communication is built using the ADKAR approach to address change management in organizations. The scope of the communication plan addresses initial phases of the ADKAR framework, i.e. 'awareness' and 'desire to participate' steps, that fits with the objectives and organization of the CREDOS project.

Isambert, E.

"THE CREDOS PROJECT: STAKEHOLDER SEGMENTATION MODEL"

D5-3, September 2007.

This document contains the generic Stakeholder Segmentation Model for the development and implementation of reduced separations for flight departure operations targeted by the CREDOS project (favorable crosswind conditions) for European airports. Segmentation means here categorizing the various parties having an interest (Stakeholders) in the development, implementation or execution of these operations according to a set of criteria. The analysis along different viewpoints shows that a

common 'interest' for CREDOS operations exist for the enhancement of airport operations through decrease of departure delay and the increase of airport productivity.

Ishii, K., Kuwahara, K. and Liu, C. H.

"NAVIER-STOKES CALCULATIONS FOR VORTEX RINGS IN AN UNBOUNDED DOMAIN"

Computers Fluids, Vol. 22, No. 4/5, 1993, pp. 589-605.

A computational code for the vorticity-potential method is developed for a three-dimensional bounded vorticity field. The evaluation of the boundary data for the vector potential in the code is improved so that the numerical solution simulates that in an unbounded domain to a high order. The time evolution of two vortex rings and that of an elliptic ring are investigated with this code. The cut-and-connect phenomena of vortex rings are successfully captured. The results are compared with those of asymptotic theory and the experiment. They also highlight the need for additional theoretical and numerical investigations.

Ishii, K., Nihei, T. and Adachi, S.

"ACCURATE NUMERICAL SIMULATION OF THREE-DIMENSIONAL LID-DRIVEN CAVITY FLOWS WITH DIFFERENT SPAN LENGTHS"

In Vortex Dominated Flows, edited by D. Blackmore, E. Krause and C. Tung, 2005, World Scientific, New Jersey, Chapter 5, pp. 87-98.

The steady incompressible vortical flows at the Reynolds number of 850 in three-dimensional lid-driven rectangular cavities with square cross sections and different span lengths are studied using a combined compact finite difference scheme with high accuracy and spectral-like resolution. The simulations have been done at the span wise aspect ratios of 1, 3, 4, 5 and 6.55. The results of 1, 3 and 4 shows that the streamlines in the cavities are chaotic and a streamline occupies the whole flow region. On the other hand, the tori of streamlines are found near the symmetric plane in the cavities with longer spans at aspect ratios of 5 and 6.55, though the global chaotic streamlines are also observed along the central axis of the cavity and around the tori.

Ishiko, K., Hashimoto, A., Matsuo, Y. and Watanabe, S.

"NUMERICAL EXAMINATION OF THE EFFECT OF CROSS-WIND ON JET BLAST"

AIAA Paper No. 2012-0862, January 2012, Nashville, Tennessee.

The runways A and B of Tokyo international airport (Haneda airport) have a cross over point. When an aircraft takes off from the runway A, it may be possible at this cross over point that the jet blast from the aircraft constitutes a hazard for another aircraft landing on the runway B. Therefore, it is required for operational safety and for improvement of capacity and efficiency of air traffic control to predict the trajectory of long-distance jet blast with high accuracy. To examine the far-field velocity of jet blast by

computational fluid dynamics in this research, simulation using Reynolds averaged Navier-Stokes equation is carried out with very large computational domain. The velocity profiles obtained by numerical simulation agree well with those obtained by experiments. Then, we perform the parametric study of wind direction. It is found that the wind direction angle that has the most effect on the deflection of jet blast is lower than ninety degrees. Moreover, the trajectory of jet blast can be described by power law.

Ishiko, K., Hashimoto, A., Matsuo, Y. and Watanabe, S.

"NUMERICAL STUDY OF THE EFFECTS OF CROSSWIND ON THE JET BLAST DEFORMATION"

ICAS Paper 2012-10.10.3, September 2012, Brisbane, Australia.

In Tokyo international airport (Haneda airport), runways A and B have a cross over point. At this point, it may be possible that the jet blast of aircraft on takeoff from the runway A constitutes a hazard for another aircraft landing on runway B. For operational safety and for improvement of capacity and efficiency of air traffic control, it is required to predict the trajectory of long-distance jet blast with high accuracy. To examine far-field velocity of jet blast by computational fluid dynamics, simulation using Reynolds averaged Navier-Stokes equation is carried out with very large computational domain in this research. The velocity profiles obtained by numerical simulation agree well with those obtained by experiments. Then, we perform the parametric study of wind direction. It is found that the wind direction angle that has more effect on the deflection of jet blast is lower than ninety degrees. Moreover, the trajectory of jet blast can be described by power law.

Ishiko, K., Hashimoto, A., Matsuo, Y. and Yoshizawa, A.

"NUMERICAL ANALYSIS OF THREE-DIMENSIONAL WALL JET USING ANISOTROPIC TURBULENCE MODEL"

AIAA Paper 2013-0268, January 2013, Grapevine, TX.

In order to predict the flow field of three-dimensional wall jets, an anisotropic constitutive relation is incorporated into the Spalart-Allmaras turbulence model. A modification of the model for the improvement of the predictability of free jets is employed. FaST Aerodynamic Routines (FaSTAR) developed by JAXA is used as a compressible-flow solver. Firstly, a turbulent boundary layer flow along a flat plate is computed to confirm the validity of the anisotropic constitutive relation. The obtained logarithmic velocity profile agrees well with the analytical solution, regardless of whether the anisotropy of the Reynolds stress is considered or not. As a result, the modification is confirmed to have no adverse effects on the prediction of the typical wall-bounded flow. Secondly, computations of three-dimensional free and wall jets are performed. For free jets, the computed results appropriately give the streamwise decay and the half-width of the velocity, confirming the applicability of the modification for free jets. For wall jets, the present model properly reproduces the secondary flow observed in the experiment, and the computed ratio of two half-widths in the lateral direction is shown to be improved by taking the anisotropic constitutive relation into account. The anisotropic constitutive relation is then used to extend the Shear-Stress Transport turbulence model. The better

results of the velocity half-widths are obtained using the different model parameters of the anisotropic constitutive relation rather than the use of the original values.

Ishimitau, K. K., VanDevender, N., Dodson, R., Brault, P.C. and Byers, B. A.

"DESIGN AND ANALYSIS OF WINGLETS FOR MILITARY AIRCRAFT"

AFFDL-TR-76-6, February 1976, Boeing Commercial Airplane Company, Seattle, WA.

A study of the design and analysis of winglets for Military Aircraft has been completed. The program consisted of investigating analytically winglet concepts for application to the KC-135 and C-141, designing and building winglets for an 0.035 and 0.070 scale model KC-135, and conducting a structural feasibility investigation of the winglet installation on the KC-135. The analysis of the winglets showed a 14 percent reduction in induced drag for the KC-135 and a 11 percent reduction for the C-141. The structural design study of the KC-135A winglet installation estimated a 592lb weight increase. An 8.4 percent improvement was estimated in $M(L/D)$ sub MAX and an 8.1 percent improvement in range factor for the KC-135A. An 0.070 scale half span KC-135 wind tunnel model has been tested in the NASA 8 Ft Transonic Tunnel. Preliminary unpublished test data have substantiated the analytical procedures used by The Boeing Company to determine the aerodynamic characteristics and performance benefits from winglets on the KC-135 aircraft.

Ishimitsu, K. K. and Zanton, D. F.

"DESIGN AND ANALYSIS OF WINGLETS FOR MILITARY AIRCRAFT: PHASE II"

AFFDL-TR-77-23, May 1977, Boeing Commercial Airplane Company, Seattle, WA.

A study of the design and analysis of winglets for military aircraft has been completed. This study is a continuation of the work reported in AFFDL-TR-76-6. The program consisted of investigating analytically the AFFDL/Boeing winglet on the take-off and landing configuration of KC-135A. Also investigated analytically were the effect of a wing leading-edge device on the performance of the AFFDL/Boeing winglets and the design of a compromise high-speed/low-speed winglet. Two wind tunnel tests were conducted by the NASA-Langley Research Center 9-foot transonic tunnel. A high-speed and low-speed test were conducted to determine the effect of the AFFDL/Boeing winglets on the KC-135A's aerodynamic performance and longitudinal and lateral-directional stability. A preliminary plan for a KC-135A winglet retrofit program was developed and its cost estimated. Based on a 1979 program start, the retrofit costs would be recovered by the start of 1984.

Ismadi, M.-Z. P., Meunier, P., Fouras, A. and Hourigan, K.

"EXPERIMENTAL CONTROL OF VORTEX BREAKDOWN BY DENSITY EFFECTS"

Physics of Fluids, Vol. 23, 2011, pp. 034104-1 - 034104-9.

The vortex breakdown inside a cylinder with a rotating top lid is controlled experimentally by injecting at the bottom a fluid with a small density difference. The density difference is obtained by mixing a heavy dye or alcohol with water to create a jet denser or lighter than water. The injection of a heavy fluid creates a buoyancy force downward, which counteracts the meridional recirculation in the cylinder and thus enhances the formation of a vortex breakdown bubble. The stability diagram shows that even a very small density difference of 0.02% can decrease by a factor of 2 the critical Reynolds number of appearance of the breakdown. On the other hand, the injection of a lighter fluid does not destroy the vortex breakdown. However, for density differences larger than 0.03%, the lighter fluid can pierce through the bubble and leads to a new structure of the vortex breakdown. Finally, a parallel is drawn between a light jet and a vortex ring generated at the bottom of the cylinder: strong vortex rings can pierce through the bubble, whereas weak vortex rings are simply advected around the bubble.

Israel, D. R.

"AN OVERVIEW OF THE UPGRADED THIRD GENERATION AIR TRAFFIC CONTROL SYSTEM"

EASCON '74 Record, IEEE Electronics and Aerospace Systems Conference, 1974, pp. 244-249

With the continuing growth of aviation, improvements to our current air traffic control system will be required. The system planned for use in the 1980's and beyond is now known as the Upgraded Third Generation System. It is designed to meet the FAA's goals of: (a) maintaining or improving safety, (b) constraining or reducing costs, and (c) increasing or improving performance. The system will be characterized by nine major features - Intermittent Positive Control, the Discrete Address Beacon System, Area Navigation, Microwave Landing System, Increased Automation, Airport Surface Traffic Control, a Wake Vortex Avoidance System, Flight Service Stations, and Aeronautical Satellites.

Israel, D. R.

"WAKE VORTEX PROGRAM STATUS"

Inter. Air Trans. Conf., Am. Soc. Civil Engineers, San Francisco, CA, March 1975, pp. 143-160

The paper describes past results, present status, and future outlook and approaches of programs for studying wake vortex behavior and reduction of its effects. The main characteristics of several vortex sensing systems are examined, including a pulsed acoustic vortex sensing system, a Doppler acoustic sensing system, a ground wind sensing system, and a laser Doppler system. Three stages in the life of an aircraft wake have been discerned by recent study: the inviscid wake stage, the entraining wake stage, and the decaying wake stage. A prototype vortex advisory system for a large airport is described.

Ito, Y.

"DESIGN AND PERFORMANCE OF AN ACOUSTIC ANTENNA FOR A PHASED ARRAY DOPPLER SODAR"

Meteorological Applications, Vol. 5, 1997, pp. 149-156.

An acoustic array antenna which has a narrow main lobe and suppressed sidelobes is studied. The directivity function formed by the multiple point sources is used to estimate the aperture of an array and the spacing between the transducer elements to make a desired beam. Then the aperture tapering based on a Chebyshev distribution and the effect of an acoustic shield are evaluated to suppress the sidelobe radiation. The total performance of the phased array system has been examined by comparison with tower instruments. The field test shows that the measured beam pattern agrees with the calculated one and the sodar-derived winds have a correlation of 0.96 and a standard deviation of differences of about 0.47-0.52 m/s compared with in situ measurements. These statistical values are as good as or even better than those from the previous experiments.

Itoh, E. and Mitici M.

"EVALUATING THE IMPACT OF NEW AIRCRAFT SEPARATION MINIMA ON AVAILABLE AIRSPACE CAPACITY AND ARRIVAL TIME DELAY"

The Aeronautical Journal, Vol. 124, No. 1274, April 2020, pp. 447-471

Although the application of new, reduced aircraft separation minima can directly increase runway throughput, the impact thereof on the traffic flow of aircraft arriving at the destination airport has not been discussed yet. This paper proposes a data-driven and queue-based modeling approach and presents an analysis of the impact on the delay time of arriving aircraft in the airspace within a radius of 100 nautical miles around an airport. The parameters of our queuing model were estimated by analyzing the data contained in the radar tracks and flight plans for flights that arrived at Tokyo International Airport during the 2 years of 2016 and 2017. The results clarified the best arrival strategy according to the distance from the arrival airport: The combination of airspace capacity control and reduction of the flight time and separation variance is the most powerful solution to mitigate delays experienced by arriving traffic while also allowing an increase in the amount of arrival traffic. The application of new wake vortex categories would enable us to increase the arrival traffic to 120%. In addition, the arrival delay time could be minimized by implementing the proposed arrival traffic strategies together with automation support for air traffic controllers.

Iungo, G. V.

"EXPERIMENTAL CHARACTERIZATION OF WIND TURBINE WAKES: WIND TUNNEL TESTS AND WIND LIDAR MEASUREMENTS"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 149, 2016, pp. 35-39.

The characterization of wind turbine wakes produced for different loading conditions of the turbine and incoming wind is a crucial task for design of wind farm layout. Indeed, the optimization of the power harvested from a wind farm can only be achieved if detrimental wake interactions are carefully inhibited or mitigated. In this paper the importance of performing wind turbine wake measurements is emphasized through two experiments, which are complementary for the experimental measurement techniques used and scientific results achieved. First, wind tunnel tests of a down-scaled wind turbine

are presented, for which fixed-point turbulence measurements are leveraged to predict the hub vortex instability encountered in the near wake. The second experiment consists in wind LIDAR measurements of the wake produced by a utility-scale wind turbine under different regimes of the atmospheric thermal stability. It is shown that wind turbine wakes recover faster under convective conditions than for neutral ones.

Iungo, G. V. and Porte-Agel, F.

"MEASUREMENT PROCEDURES FOR CHARACTERIZATION OF WIND TURBINE WAKES WITH SCANNING DOPPLER WIND LIDARS"

Advances in Science and Research, Vol. 10, 2013, pp. 71-75.

The wake flow produced from an Enercon E-70 wind turbine is investigated through three scanning Doppler wind LiDARs. One LiDAR is deployed upwind to characterize the incoming wind, while the other two LiDARs are located downstream to carry out wake measurements. The main challenge in performing measurements of wind turbine wakes is represented by the varying wind conditions, and by the consequent adjustments of the turbine yaw angle needed to maximize power production. Consequently, considering possible variations of the relative position between the LiDAR measurement volume and wake location, different measuring techniques were carried out to perform 2-D and 3-D characterizations of the mean wake velocity field. However, larger measurement volumes and higher spatial resolution require longer sampling periods; thus, to investigate wake turbulence tests were also performed by staring the LiDAR laser beam over fixed directions with the maximum sampling frequency. The characterization of the wake recovery along the downwind direction is performed. Moreover, wake turbulence peaks are detected at turbine top-tip height, which can represent increased fatigue loads for downstream wind turbines within a wind farm.

Iungo, G. V., Skinner, P. and Buresti, G.

"CORRECTION OF WANDERING SMOOTHING EFFECTS ON STATIC MEASUREMENTS OF A WING-TIP VORTEX"

Exp. Fluids, Vol. 46, 2009, pp. 435-452

Wandering is a typical feature of wing-tip vortices and it consists in random fluctuations of the vortex core. Consequently, vortices measured by static measuring techniques appear to be more diffuse than in reality, so that a correction method is needed. In the present paper statistical simulations of the wandering of a Lamb-Oseen vortex are first performed by representing the vortex core locations through bi-variate normal probability density functions. It is found that wandering amplitudes smaller than 60 percent of the core radius are well predicted by using the ratio between the RMS value of the mean cross-velocity and its slope measured at the mean vortex center. Furthermore, the principal axes of wandering can be accurately evaluated from the opposite of the cross-correlation coefficient between the spanwise and the normal velocities measured at the mean vortex center. The correction of the wandering smoothing effects is then carried out through four different algorithms that perform

the deconvolution of the mean velocity field with the probability density function that represents the wandering. The corrections performed are very accurate for the simulations with wandering amplitudes smaller than 60 percent of the core radius, whereas errors become larger with increasing wandering amplitudes. Subsequently, the whole procedure to evaluate wandering and to correct the mean velocity field is applied to static measurements, carried out with a fast-response five-hole pressure probe, of a tip vortex generated from a NACA 0012 half-wing model. It is found that the wandering is predominantly in the upward-outboard to downward-inboard direction. Furthermore, the wandering amplitude grows with increasing streamwise distance from the wing, whereas it decreases with increasing angle of attack and free-stream velocity.

Iungo, G. V., Wu, Y.-T. and Porte-Agel, F.

"FIELD MEASUREMENTS OF WIND TURBINE WAKES WITH LIDARS"

Journal of Atmospheric and Oceanic Technology, Vol. 30, February 2013, pp. 274-287.

Field measurements of the wake flow produced from a 2-MW Enercon E-70 wind turbine were performed using three scanning Doppler wind lidars. A GPS-based technique was used to determine the position of the wind turbine and the wind lidar locations, as well as the direction of the laser beams. The lidars used in this study are characterized by a high spatial resolution of 18 m, which allows the detailed characterization of the wind turbine wake. Two-dimensional measurements of wind speed were carried out by scanning a single lidar over the vertical symmetry plane of the wake. The mean axial velocity field was then retrieved by averaging 2D scans performed consecutively. To investigate wake turbulence, single lidar measurements were performed by staring the laser beam at fixed directions and using the maximum sampling frequency. From these tests, peaks in the velocity variance are detected within the wake in correspondence of the turbine top tip height; this enhanced turbulence could represent a source of dangerous fatigue loads for downstream turbines. The spectral density of the measured velocity fluctuations shows a clear inertial-range scaling behavior. Then, simultaneous measurements with two lidars were performed to characterize both the axial and the vertical velocity components. For this setup, the two velocity components were retrieved only for measurement points for which the two laser beams crossed nearly at a right angle. Statistics were computed over the sample set for both velocity components, and they showed strong flow fluctuations in the near-wake region at turbine top tip height, with a turbulence intensity of about 30 percent.

Ivanell, S., Mikkelsen, R., Sorensen, J. N. and Henningson, D.

"STABILITY ANALYSIS OF THE TIP VORTICES OF A WIND TURBINE"

AIAA Paper No. 2008-1322, Reno, NV, January 2008

The aim of the present project is to get a better understanding of the stability properties of wakes generated by wind turbine rotors. To determine the stability properties of wind turbine wakes a numerical study on the stability of the tip vortices behind the Tjaereborg wind turbine has been carried out. The numerical model is based on large eddy simulations of the Navier-Stokes equations using the

actuator line method to generate the wake and the tip vortices. To determine critical frequencies the flow is perturbed by inserting a harmonic perturbation. The results show that the instability is dispersive and that growth arise only for some specific frequencies and type of modes.

Ivanov, S. V.

"MICROWAVE ABSORPTION SPECTRA OF THE ATMOSPHERE AND AIRCRAFT WAKE"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 329-339

Absorption spectra of the atmospheric air and aircraft wake are analyzed within 1-1000 GHz spectral region to estimate possibilities of aircraft vortex wake visualization from emission or absorption of the microwave radiation. The standard atmosphere and Boeing 707 aircraft wake conditions are considered regarding the gaseous components (oxygen, nitrogen, water, small gas constituents) and probable presence of water aerosol and raindrops. The Liebe MPM model is used for the oxygen, nitrogen, water, aerosol, and rain attenuation calculation. Absorption of trace gases is modeled using the HITRAN-96 database. Absorption of water dimers is calculated separately and its contribution to continuum is discussed. Water vapor is found to be a suitable exhaust gas for the aircraft wake visualization in microwave region.

Ivanov, S. V.

"SPECTROSCOPIC DETECTION OF AIRCRAFT WAKE GASES"

Physics of Wave Phenomena, Vol. 15, No. 1, 2007, pp. 57-65.

Using the technique of limiting information-metric scales, the potential of laser IR absorption spectroscopy for detecting small gas components of aircraft wake was quantitatively analyzed. Formulas for minimum distinguishable and minimum detectable gas concentrations were derived. Calculation was carried out for SO₂, NO, and NO₂ under typical conditions near the Boeing 707 aircraft engine nozzle at altitude $H = 12.2$ km. Alternative IR laser spectroscopy methods for detecting various gas components in the near wake were considered. Two possibilities to improve the concentration measurement sensitivity were analyzed: (i) a decrease in the background absorption of CO₂ and H₂O and (ii) an increase in the absorption cross section of detected gas.

Iversen, J. D.

"CORRELATION OF TURBULENT TRAILING VORTEX DECAY DATA"

Journal of Aircraft, Vol. 13, No. 5, May 1976, pp. 338-342

A correlation function, derived based on self-similar variable eddy-viscosity decay, is introduced and utilized to correlate aircraft trailing vortex velocity data from ground and flight experiments. The correlation function collapses maximum tangential velocity data from scale-model and flight tests to a

single curve. The resulting curve clearly shows both the inviscid plateau and the downstream decay regions. A comparison between experimental data and numerical solution shows closer agreement with the variable eddy viscosity solution than the constant viscosity analytical solution.

Iversen, J. D.

"STUDIES OF VORTEX DECAY AND VORTEX ROLLUP"

Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, Air Force Flight Dynamics Laboratory, AFFDL-TM-75-16-FGC, 1974, pp. 50-58

The effect of generating aircraft span loading on the following aircraft rolling moment is discussed for the particular cases of tailored loading, sawtooth loading and unconventional flap loading on the generating aircraft. A correlation function is introduced with correlates maximum tangential velocity in the vortex with downstream distance for a wide range of Reynolds numbers.

Iversen, J. D.

"INVISCID TO TURBULENT TRANSITION OF TRAILING VORTICES"

ISU-ERI-AMES-74241, November 1974, Iowa State University, Ames, IA

It has been discovered experimentally that a so-called 'plateau' region exists in the vortex system which trails from a lifting wing. The decay of the vortex due to viscous or turbulent shear is very slow in the plateau so that the maximum tangential speed in the vortices remains very nearly constant for some distance downstream of roll-up and then begins to decrease, becoming inversely proportional to the square root of the distance far downstream.

Iversen, J. D.

"INVISCID TO TURBULENT TRANSITION OF TRAILING VORTICES"

AIAA Paper No. 1975-0883, Hartford, CT, June 1975.

The plateau region in which trailing vortices initially exhibit slow decay of maximum tangential speed is demonstrated with the aid of constant and variable eddy viscosity models. The existence of the plateau is explained by the presence of the viscous core and by the necessity for transition of the initial, nearly inviscid profile to similarity far downstream. Span loading is shown to affect the initial maximum tangential speed as well as the duration of the plateau region. Triangular span loading is shown to present less hazard to trailing aircraft, at least in the near field, than elliptic loading because the inviscid profile for triangular loading exhibits a finite tangential speed at the vortex centerline and a large inviscid core.

Iversen, J. D.

"TRAILING VORTEX EFFECTS ON FOLLOWING AIRCRAFT"

ISU USAF Operations Analysis Report, ERI-66200, 1971, Iowa State University, Ames, IA

Wind tunnel tests of two C-130 aircraft models were performed to determine the effect of the wake of a leading aircraft upon the aerodynamic forces experienced by the trailing aircraft. The results of the tests along with theoretical considerations are used to calculate lift forces and rolling moments experienced by the trailing aircraft.

Iversen, J. D. and Bernstein, S.

"DYNAMIC SIMULATION OF AN AIRCRAFT UNDER THE EFFECT OF VORTEX WAKE TURBULENCE"

Annales de l'Association Pour le Calcul Analogique, Vol. 14, 1972, pp. 136-144

The introduction of modern heavy jets poses an increasing hazard to light and moderate weight aircraft due to high-intensity vortex wake turbulence. A technique is developed to simulate the responses of a trailing aircraft due to the induced rolling moments and loss of lift imposed by the vortices. Despite the nonlinear and complex nature of the problem, the method was applied successfully using an EAI 8812 analog computer with no hybrid facilities. The simulated aircraft was free to roll and move vertically and laterally with respect to the generating aircraft. Results of such a simulation for the case of a C-130 behind another C-130 and behind a C-5A are presented.

Iversen, J. D. and Bernstein, S.

"TRAILING VORTEX EFFECTS ON FOLLOWING AIRCRAFT"

Journal of Aircraft, Vol. 11, No. 1, January 1974, pp. 60-61

Wind-tunnel tests and a strip-theory analysis are utilized to estimate the change in lift force and rolling moment on an aircraft due to its penetration into the vortex trail of a leading aircraft. Values of lift and rolling moment coefficients on the trailing aircraft are presented as functions of vertical and lateral displacement with respect to the vortex.

Iversen, J. D., Brandt, S. A. and Raj, P.

"MERGING DISTANCE CRITERIA FOR CO-ROTATING TRAILING VORTICES"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 161-172

The merging of co-rotational vortices of equal strength is studied by flow-visualization and hot-wire anemometer wind-tunnel experiments and by preliminary numerical calculation of vortex merging. Wind-tunnel experiments and numerical calculations indicate that the effects of turbulence and

viscosity are to decrease merging distance from that predicted by inviscid calculations. Hot-wire anemometer measurements of velocity profiles and rolling-moment measurements on a follower model show reduction of the trailing vortex hazard due to merging.

Iversen, J. D., Corsiglia, V. R., Park, S., Backhus, D. R. and Brickman, R. A.

"HOT-WIRE, LASER-ANEMOMETER, AND FORCE MEASUREMENTS OF INTERACTING TRAILING VORTICES"

Journal of Aircraft, Vol. 16, No. 7, July 1979, pp. 448-45.

Single and multiple trailing vortices shed from semispan wings and a transport model in a wind tunnel were studied by means of a laser velocimeter, hot-wire anemometer, and trailing model incorporating a six-component force balance. Velocity profile and turbulence data from the laser velocimeter and hot-wire anemometer are presented and shown to compare well with the Betz inviscid circulation model. Lift and rolling moment measurements on the following model are compared with those predicted from the flow field measurements.

Iversen, J. D., Park, S., Backhus, D. R., Brickman, R. A. and Corsiglia, V. R.

"HOT-WIRE, LASER ANEMOMETER AND FORCE BALANCE MEASUREMENTS OF CROSS-SECTIONAL PLANES OF SINGLE AND INTERACTING TRAILING VORTICES"

AIAA Paper No. 1978-1194, Seattle, WA, July 197.

Single and multiple trailing vortices shed from semi-span wings and a transport model in a wind tunnel were studied by means of a laser-velocimeter, hot-wire anemometer, and a trailing model incorporating a 6-component force balance. Velocity profile and turbulence data from the laser-velocimeter and hot-wire anemometer are presented and shown to compare well with the Betz inviscid circulation model. Lift and rolling moment measurements on the following model are compared with those predicted from the flow field measurements.

Iwai, H., Ishii, S., Tsunematsu, N., Mizutani, K. Murayama, Y., Itabe, T., Yamada, I., Matayoshi, N., Matsushima, D., Sha, W., Yamazaki, T. and Iwasaki, T.

"COMPARISON OF DUAL-DOPPLER LIDAR MEASUREMENTS OF WIND WITH HELICOPTER MEASUREMENTS"

Proceedings 15th Coherent Laser Radar Conference, June 2009, Toulouse, France, pp. 103-106.

Dual-Doppler lidar and heliborne sensor were used to investigate the three-dimensional structure of the wind field over Sendai Airport in June 2007. We applied a variational method developed for multiple Doppler radar measurements to dual-Doppler lidar analysis. The comparison of wind fields retrieved from dual-Doppler analysis to wind fields measured by the JAXA heliborne sensor reveals

differences of horizontal wind speed and wind direction of 0.11 m/s and 10.1 degrees, on average, with standard deviations not exceeding 0.75 m/s and 16 degrees, respectively.

Jackel, R., Gutierrez Urueta, G. L., Tapia Rodriguez, F. and Monreal Jimenez, C.

"NUMERICAL AND EXPERIMENTAL CHARACTERISATION OF AN AERONAUTIC PITOT PROBE"

The Aeronautical Journal, Vol. 123, No. 1264, June 2019, pp. 890-911.

Aeronautic Pitot probes (PPs) are extremely important for airspeed and altitude measurements in aviation. Failure of the instrument due to clogging caused by ice formation can lead to dangerous situations. In this work, a commercial aeronautic PP was characterized experimentally regarding its inner composition, material properties and its thermal performance in a climatic wind tunnel. Performance runs were taken out to analyze the thermal response of the PP under various operating conditions with a particular emphasis on the cooling process in the case of a heating element failure. Data for the thermal conductivity, diffusivity and specific heat for each material forming the PP were obtained. A numerical model to simulate the thermal behavior of the PP was created using Comsol Multiphysics (CM). Experimental data were compared with their numerical counterparts for model validation purposes. After the model was validated, the operation of the PP in flight conditions was simulated. The failure of the conventional heating system was analyzed to obtain the time until the PP reaches a tip temperature where ice formation can be expected. The tip temperature undercut the zero degrees Celsius mark 165 seconds after the heating element was switched off. The data collected in this work can be used to implement and validate mathematical models to predict the thermal performance of Pitot probes in flight conditions.

Jackson, R. P.

"AERONAUTICS - THE BIG 'A' IN NASA"

FAA Symposium on Turbulence, Federal Aviation Administration, 1971, pp. 13-18

The paper presents highlights of the operating systems part of the NASA aeronautics program and where wake turbulence fits into NASA's scale of priorities. The roles of aircraft noise and related research are discussed.

Jackson, W., editor, Yaras, M., Harvey, J., Winckelmans, G., Fournier, G. and Belotserkovsky, A.

"WAKE VORTEX PREDICTION: AN OVERVIEW"

TP 13629E, March 2001, Transportation Development Centre, Montreal, Canada

Aviation authorities have long recognized that reducing wake vortex separations during instrument meteorological conditions could permit the capacity at major airports to be increased by up to 15 percent, and delays on arrival and departure to be significantly reduced. This improved efficiency would be worth billions of dollars in savings worldwide. The objectives of this research project were to

increase the capacity of major airports, while maintaining or improving existing levels of safety, and to continue the evaluation and development of a Vortex Forecast System (VFS), which had been under development for several years in Russia. Transport Canada formed a team of experts from Canada, Belgium, and Russia. This team has completed seven years of developing VFS, conducting related studies, and co-operating with other researchers in Europe and North America. VFS is now one of the most capable real-time wake vortex prediction systems in the world. It is recommended that development of VFS be continued. A specific airport should be selected in Canada to provide a focus for Canadian wake vortex research. Canadian stakeholders such as Transport Canada, NAV CANADA, and major airport authorities should continue wake vortex research and continue to co-operate internationally.

Jacob, D., Lai, D. Y. and Delisi, D. P.

"DEVELOPMENT OF AN IMPROVED PULSED LIDAR CIRCULATION ESTIMATION ALGORITHM AND PERFORMANCE RESULTS FOR DENVER OGE DATA"

AIAA Paper 2013-0509, January 2013, Grapevine, TX.

A new algorithm for estimating circulation strength of aircraft wake vortices from pulsed coherent lidar measurements is described and results from processing Out of Ground Effect (OGE) field data from NASA measurements made at the Denver International Airport in 2003 are compared to results obtained using the Lockheed Martin Spectral Space Processing (Legacy) algorithm. The key improvements of the new algorithm over the Legacy algorithm concern the (a) vortex system matched filters, (b) maximum likelihood ratio algorithm, and (c) ambient wind correction. An overview of the algorithm is presented highlighting the differences between this new algorithm and the Legacy algorithm. The performance of both algorithms will be shown for FAA Large weight-category aircraft and compared to historical circulation decay estimates for similar conditions from other field campaigns.

Jacob, D., Lai, D. Y., Delisi, D. P., Barr, K. S., Hutton, D. A., Shald, S., Hannon, S. M. and Gatt, P.

"ASSESSMENT OF LOCKHEED MARTIN'S AIRCRAFT WAKE VORTEX CIRCULATION ESTIMATION ALGORITHMS USING SIMULATED LIDAR DATA"

AIAA Paper 2011-3196, June 2011, Honolulu, Hawaii.

A new algorithm for estimating circulation strength of aircraft wake vortices is under development by Lockheed Martin and is being evaluated by NorthWest Research Associates under the NASA Research Announcement (NASA-NRA) NextGen Airportal Program. The algorithm is being developed with the aid of Lockheed Martin's Coherent Wind Lidar Simulator, developed under the same NASA-NRA program. A brief description of the simulator tool is presented. An overview of both the legacy estimation algorithm and the new algorithm under development is presented which highlights the differences between the two algorithms. The performance of both algorithms is assessed using simulated lidar data generated from analytic wake models and Large Eddy Simulation vortex wind fields with ambient

turbulence eddy dissipation rates of 0.00004, 0.0005 and 0.0145 meters squared per second cubed. Algorithm performance is quantified in terms of standard deviation and bias of estimates as a function of SNR.

Jacob, D., Pruis, M. J., Lai, D. Y. and Delisi, D. P.

"WAKEMOD 4.1: A NEW STANDALONE WAKE VORTEX ALGORITHM FOR ESTIMATING CIRCULATION STRENGTH AND POSITION"

AIAA Paper 2015-3176, June 2015, Dallas, TX.

WakeMod 4.1 (WM41) is a new standalone algorithm for estimating circulation strength and position of aircraft wake vortices from the Lockheed Martin WindTracer spectral data product. Preliminary results of a comparison of WM41 and the Lockheed Martin Offline Wake Processing (Legacy) wake algorithm are presented. Evaluation of the WM41 algorithm was accomplished using both simulated data and field observations obtained at four different airports. There are three principal findings of this study. The first finding is that WM41 provides similar performance to Legacy for Heavy aircraft in the ability to estimate circulation strength. An additional benefit of WM41 circulation estimates is that they do not show high sensitivity to SNR, which is a known limitation of the Legacy wake algorithm. The second key finding is that WM41 and Legacy provide similar estimates regarding vortex position for Heavy and Large aircraft. Previous studies have indicated that the Legacy algorithm estimates vortex position to within 10 meters, and indications of this preliminary study is that the WM41 algorithm estimates are as good or better in that WM41 provides more consistent estimates of vortex pair orientation and spacing throughout a wake track. Furthermore, WM41 position estimates are not affected by the choice of a region of interest. The third principal finding of this study is that WM41 can detect and estimate circulation strength of weak vortices below the sensitivity limit of the Legacy algorithm (approximately 125 meters squared per second), and thereby allows for improved estimation of aircraft wake behavior for aircraft smaller than Heavy, and in the estimation of vortex strength at late wake ages when vortices are weak.

Jacob, J. D.

"EXPERIMENTAL INVESTIGATION OF THE TRAILING VORTEX WAKE OF RECTANGULAR AIRFOILS"

Ph.D. Thesis, 1995, University of California at Berkeley, Berkeley, CA

The trailing vortex wake generated by high aspect-ratio airfoils is investigated in a tow tank. DPIV is used to measure the velocities in the cross-stream plane in the laboratory reference frame as the wing is towed through the tank. The Reynolds number ranges from 20,000 to 80,000. Four sets of vortex wakes are measured: a NACA 0012, a NACA 0012 with tip-jets, a NACA 0012 with flaps and a circular arc airfoil with flaps. The natural wake is found to be very stable and long lived. Tip-jets placed on the wing affect the distribution of vorticity within the vortex core but do not affect the circulation of the vortex, though forcing does change the separation distance between the tip vortex filaments. Axial momentum injection produces instabilities on the vortex which may lead to breakup of the vortices.

The same-signed tip and flap vortices from the airfoils with deployed flaps are found to merge in all cases. In a circular arc airfoil with 30% span flaps, the geometry of the strut is found to affect the time to vortex merger. The time is doubled by using a faired flat-plate strut as opposed to a thick streamlined strut.

Jacob, J. D.

"EXPERIMENTAL INVESTIGATION OF CO-ROTATING TRAILING VORTICES"

AIAA Paper No. 1998-0590, Reno, NV, January 1998

The paper discusses preliminary results of experiments to generate a single pair of co-rotating trailing vortices and observe their behavior in a towing tank. Several configurations of lifting surfaces are used to achieve this. A laser sheet illuminates tracer particles in the flow and a digital camera is used to capture a sequence of PIV images. Planar velocity vector fields and their gradients are derived from these images using an adaptive Lagrangian parcel tracking algorithm. Iso-vorticity surfaces are extracted from time series of planar vorticity data. Reynolds numbers based on total circulation of the vortices in the present experiments range from 2500 to 10000. Merger of the co-rotating vortex pair is observed at all circulation Reynolds numbers. The relation between merger time and Reynolds number is neither constant nor monotonic however, differing from previous experiments at higher Reynolds numbers. Merger occurs from $1/4$ to $1/3$ of an orbit period for typical cases. The merger process appears to be inviscid and three-dimensional. No evidence of breakdown or strong instabilities are present.

Jacob, J. D. and Savas, O.

"VORTEX DYNAMICS IN TRAILING WAKES OF FLAPPED RECTANGULAR WINGS"

AIAA Paper No. 1997-0048, Reno, NV, January 1997

The dynamics of trailing vortex wakes from flapped airfoils are investigated in a towing tank and a wind tunnel. The wakes from a lifting rectangular circular arc airfoil with an aspect ratio of 6 and flap-spans of 30% and 67% and a NACA 0012 with an aspect ratio of 8 and flap-spans of 40% and 50% are studied as the wake evolves downstream. Chord-based Reynolds number Re_c ranged from 1.5×10^4 to 8×10^4 . A traversing five-hole pitot probe and Lagrangian Parcel Tracking (LPT) are used to measure the velocity field in a cross-stream plane behind the wing in the wind tunnel and the towing tank, respectively. The interaction of the tip and flap vortices are studied. Merger of the flap and tip vortices usually occurs within one orbit, leading to a shorter descent distance to merger for the longer flap-spans.

Jacob, J. D., Liepmann, D. and Savas, O.

"NATURAL AND FORCED GROWTH CHARACTERISTICS OF THE VORTEX WAKE OF A RECTANGULAR AIRFOIL"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 27-1 to 27-12

The forced trailing vortex wake of a rectangular NACA 0012 airfoil with an aspect ratio of 8 is investigated experimentally. The experiments include limited five-hole probe measurements in the near wake in a wind tunnel and extensive DPIV measurements in the far wake in a tow tank. Measurements are conducted on the natural wake and the forced wake at chord Reynolds numbers from 2×10^4 to 6×10^4 . The wake is forced by axial jets located on each wing-tip injecting fluid into the vortex cores. The forcing is steady or pulsatile. Pulsatile forcing is varied from 1 Hz to 40 Hz and with the wing-tip jets in phase, out of phase, or one on/one off. Relevant parameters, including vortex separation, vorticity, circulation, and core size, are measured up to 1000 chord lengths behind the wing. Forcing increases both the separation of the vortex pair and the growth rate of the vortex core size. At low frequencies, these effects are monotonic with increasing forcing frequency. At high frequencies, the measurements suggest a complex response to forcing. Based on measurements and observations, some parameters of importance are suggested in exploring possible means of controlling the behavior of the vortex wake. The complexity of the problem dictates that any search for identifying practical solutions must be a concerted effort among experiments, analyses and numerics.

Jacob, J. D., Liepmann, D. and Savas, O.

"EXPERIMENTAL INVESTIGATION OF THE TRAILING VORTEX WAKE OF A RECTANGULAR WING"

AIAA Paper No. 1995-1841, San Diego, CA, June 1995.

The trailing vortex wake behind an NACA 0012 rectangular airfoil is investigated to establish the general nature of both the near and far field wake for further experimental exploration of the stability characteristics. Measurements of the wake are made up to 250 spans downstream of the airfoil with $20,000 < Re < 60,000$. Velocity, vorticity, and circulation are determined by digital particle image velocimetry. It is found that the wake is extremely stable and long-lived. The motion of the vortex pair is steady. The growth of the vortex core and corresponding circulation shows no appreciable decay over the measurement period. No short- or long-wave instabilities are observed in the naturally evolving vortex wake.

Jacob, J. D., Savas, O. and Liepmann, D.

"EXPERIMENTAL INVESTIGATION OF FORCED WAKE VORTICES OF A RECTANGULAR WING"

AIAA Paper No. 1996-2497, New Orleans, LA, June 1996

The forced trailing vortex wake of a rectangular NACA 0012 airfoil with an aspect ratio of 8 is investigated. Measurements are conducted on the natural wake and the forced wake at chord Reynolds numbers from 20,000 to 60,000. The wake is forced by axial jets located on each wing-tip

injecting fluid into the vortex cores. The forcing is steady or pulsatile. Pulsatile forcing is varied from 1 to 40 Hz and with the wing-tip jets in phase, out of phase, or one on/one off. Relevant parameters, including vortex separation, vorticity, circulation, and core size, are measured up to 1000 chord lengths behind the wing. Forcing increases both the separation of the vortex pair and the growth rate of the vortex core size. At low frequencies, these effects are monotonic with increasing forcing frequency. At high frequencies, the measurements suggest a complex response to forcing.

Jacob, J. D., Savas, O. and Liepmann, D.

"AIRCRAFT WAKE TURBULENCE AND AIRPORT CAPACITY"

Institute of Transportation Studies Review, Vol. 19, No. 4, August 1996, pp. 2-3, 5

Currently, the distance that must be maintained between aircraft when instrument flight regulations are in effect ranges from 2.5 nautical miles to 6 nautical miles, depending on the size of the aircraft and prevailing weather conditions. With a better understanding of wake vortices, we may be able to predict how far behind an aircraft the wake remains a threat, and to develop techniques that will cause the wake to dissipate more quickly. It might then be possible to reduce the FAA's current separation standards, thereby increasing the capacity of airports around the world.

Jacob, J. D., Savas, O. and Liepmann, D.

"TRAILING VORTEX WAKE GROWTH CHARACTERISTICS OF A HIGH ASPECT RATIO RECTANGULAR AIRFOIL"

AIAA Journal, Vol. 35, No. 2, February 1997, pp. 275-280

The growth characteristics of trailing vortex wakes are investigated in a towing tank. The wakes from a lifting rectangular NACA 0012 airfoil with an aspect ratio of 8 are studied up to 1400 chords downstream. The circulation Reynolds number ranged from 4,000 to 40,000. Digital particle image velocimetry is used to measure the velocity field in the cross-stream plane from which vorticity is calculated. The vortex pair is observed to be very stable and long-lived, showing little decay in the circulation of the individual vortices. The vorticity, however, diffuses over time within the cores of the vortices. The growth is found to be reminiscent of laminar diffusion. No Crow instabilities are observed within the range of these measurements.

Jacob, J., Savas, O. and Liepmann, D.

"TRAILING VORTEX WAKE GROWTH CHARACTERISTICS OF A HIGH ASPECT RATIO RECTANGULAR AIRFOIL"

AIAA Journal, Vol. 35, No. 2, February 1997, pp. 275-280

The growth characteristics of trailing vortex wakes are investigated in a towing tank. The wakes from a lifting rectangular NACA 0012 airfoil with an aspect ratio of 8 are studied up to 1400 chords

downstream. The circulation Reynolds number ranged from $4 \times 1,000$ to $4 \times 10,000$. Digital particle image velocimetry is used to measure the velocity field in the cross-stream plane from which vorticity is calculated. The vortex pair is observed to be very stable and long-lived, showing little decay in the circulation of the individual vortices. The vorticity, however, diffuses over time within the cores of the vortices. This growth is found to be reminiscent of laminar diffusion. No Crow instabilities are observed within the range of these measurements.

Jacobsen, R. A.

"HOT-WIRE ANEMOMETRY FOR IN-FLIGHT MEASUREMENT OF AIRCRAFT WAKE VORTICES"

Proceedings Fifth Annual Symposium, Society of Flight Test Engineers, 1974, pp. 4/13-4/24

An airborne hot-wire anemometry system capable of providing data with few limitations has been used in several flight studies. The design features of the technique and the operational experience with it are described. The development program has resulted in a flight-test technique that can make accurate velocity measurements in flow regimes where large velocity gradients occur.

Jacobsen, R. A.

"HOT-WIRE ANEMOMETRY FOR IN-FLIGHT MEASUREMENT OF AIRCRAFT WAKE VORTICES"

DISA Information, April 1977, pp. 21-27

A development program has demonstrated that hot-wire anemometry can be used successfully on an aircraft in flight to make measurements of wake vortices produced by another aircraft. The probe, whose wires were made of platinum/rhodium, 10 microns in diameter, provides unambiguous results for inflow angles less than about 35 deg. off the probe axis. The high frequency response capability of the hot-wire system allows detailed measurement of the flow structure, and the study of aircraft hazards associated with wake turbulence.

Jacobsen, R. A. and Barber, M. R.

"FLIGHT TEST TECHNIQUES FOR WAKE-VORTEX MINIMIZATION STUDIES"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 193-220

Flight test techniques developed for use in a study of wake turbulence and used recently in-flight studies of wake minimization methods are discussed. Flow visualization was developed as a technique for qualitatively assessing minimization methods and is required in flight test procedures for making quantitative measurements. The quantitative techniques are the measurement of the upset dynamics of an aircraft encountering the wake and the measurement of the wake velocity profiles. Descriptions of the instrumentation and the data reduction and correlation methods are given.

Jacobsen, R. A. and Drinkwater, F. J.

"EXPLORATORY FLIGHT INVESTIGATION OF AIRCRAFT RESPONSE TO THE WING VORTEX WAKE GENERATED BY THE AUGMENTOR WING JET STOL RESEARCH AIRCRAFT"

NASA TM-X-62387, May 1975, NASA Ames Research Center, Moffett Field, CA

A brief exploratory flight program was conducted at Ames Research Center to investigate the vortex wake hazard of a powered-lift STOL aircraft. The study was made by flying an instrumented Cessna 210 aircraft into the wake of the Augmentor Wing Jet STOL research aircraft at separation distances from 1 to 4 n.mi. Characteristics of the wake were evaluated in terms of the magnitude of the upset of the probing aircraft. Results indicated that within 1 n.mi. separation the wake could cause rolling moments in excess of roll control power and yawing moments equivalent to rudder control power of the probe aircraft. Subjective evaluations by the pilot of the Cessna 210 aircraft, supported by response measurements, indicated that the upset caused by the wake of the STOL aircraft was comparable to that of a DC-9 in the landing configuration.

Jacobsen, R. A. and Short, B. J.

"A FLIGHT INVESTIGATION OF THE WAKE TURBULENCE ALLEVIATION RESULTING FROM A FLAP CONFIGURATION CHANGE ON A B-747 AIRCRAFT"

NASA TM 73263, July 1977, NASA Ames Research Center, Moffett Field, CA

A flight test investigation was conducted to evaluate the effects of a flap configuration change on the vortex wake characteristics of a Boeing 747 (B-747) aircraft as measured by differences in upset response resulting from deliberate vortex encounters by a following Learjet aircraft and by direct measurement of the velocities in the wake. The flaps of the B-747 have a predominant effect on the wake. The normal landing flap configuration produces a strong vortex that is attenuated when the outboard flap segments are raised; however, extension of the landing gear at that point increases the vortex induced upsets. These effects are in general agreement with existing wind tunnel and flight data for the modified flap configuration.

Jacquin, L.

"AIRCRAFT TRAILING VORTICES: AN INTRODUCTION"

C. R. Physique, Vol. 6, 2005, pp. 395-398

Flow momentum that is deflected in a persistent way by a wing, or by another flow, becomes organized in coherent and energetic vortex structures. This phenomenon is briefly introduced here by comparison with other phenomena such as the production of vortices by impulsive forces (e.g. during animal flight), or the production of turbulence by jets. These considerations aim at underlining the fundamental nature of this strange mechanism, which is usually hidden behind engineering models produced by aerodynamic science. The control of these mechanisms, for applications to the safety of the airplanes for example, opens a vast multidisciplinary field of research.

Jacquín, L.

"ON TRAILING VORTICES: A SHORT REVIEW"

International Journal of Heat and Fluid Flow, Vol. 26, Issue 6, December 2005, pp. 843-854.

This paper reviews some mechanisms involved in the dynamics of vortices in fluid flows. The topic is first introduced by pointing out its importance in aerodynamics. Several basic notions useful to appraise experimental observations are then surveyed, namely: centrifugal instabilities, inertial waves, cooperative instabilities, vortex merger, vortex breakdown and turbulence in vortices. Each topic is illustrated with experimental or numerical results.

Jacquín, L. and Garnier, F.

"ON THE DYNAMICS OF ENGINE JETS BEHIND A TRANSPORT AIRCRAFT"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 37-1 to 37-8

The various mechanisms that contribute to the mixing and dispersion of the engine exhausts through their interaction with the vortex wake of an aircraft are discussed. The case of a typical large transport aircraft is considered. First, the interaction between the jets and the vortices is characterized by means of non-dimensional parameters. When considering aircraft under cruise conditions, it is shown the jets have almost no effect on the vortex wake dynamics. We then consider the way the jet is changed by the vortices. This is evaluated by means of an integral model. Examples are given which show that the jet is captured by the vortices at very different distances behind the aircraft depending on the engine-wingtip separation. The model does not consider the distortion of the jet plume by the vortex shearing which becomes significant when the jet reaches the vortex center region. Results of a numerical simulation of the convection-diffusion of a passive scalar field, as well as a visualization realized during an experiment are presented in order to illustrate this point.

Jacquín, L. and Pantano, C.

"ON THE PERSISTENCE OF TRAILING VORTICES"

J. Fluid Mech., Vol. 471, 2002, pp. 159-168

The short-wave stability properties of a Batchelor vortex are used to explain the intrinsic resistance of vortices to turbulent diffusion. We show that turbulence produced within the vortex core has to overcome a stabilizing 'dispersion buffer', where energy of the perturbations is dispersed by inertial waves without interfering with the mean flow, before they can reach the periphery of the vortex. While angular momentum is maintained by this mechanism, the difference in energy extraction by turbulence from the axial and tangential velocity fields due to a lack of alignment between the mean and turbulent strain tensors, a typical effect of flow rotation or curvature, leads to stabilization through

a progressive damping of the axial shear in the vortex core. We show that the efficiency of these stabilizing mechanisms depends on the swirl number, the ratio between the maximum tangential velocity and the axial velocity difference. If the swirl parameter is low enough, turbulence is able to reach the vortex periphery and a small circulation overshoot develops, leading to weak diffusion of angular momentum outward.

Jacquín, L., Fabre, D. and Sipp, D.

"STABILITY PROPERTIES AND UNSTEADINESS OF WAKE VORTICES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Propagation of inertial waves and amplification of co-operative instabilities are basic linear mechanisms which lead to unsteadiness in trailing wake vortices. In a wind tunnel, where only a small downstream distance is usually surveyed, these unsteady phenomena lead to displacements of the vortices, which are of small amplitude but which can be measured thanks to the presence of very sharp velocity gradients within the vortices. The most promising way to produce less harmful wakes behind an aircraft is to promote the long-wave co-operative instabilities which may develop in a system of several, at least two, vortices and which lead to destructive interactions between the two halves of the wake. Such instabilities may be quantified through considering the stability of vortex filaments and by neglecting the detailed structure of the vortex cores. The respective properties of different configurations will be discussed with the objective to define optimal vortex arrangements which lead to significant amplification of initial perturbations. Short-wave instabilities are also relevant in applications because these instabilities are known to play a dominant role in the merger of the vortices. A detailed description of the vortex core structure becomes now necessary for characterizing instabilities which develop on scales of the order of the vortex core width. This will be discussed considering experimental observations and theoretical analysis. In particular, it will be shown that the basic flows involving only one length scale, e.g. the Rankine vortex or the Lamb-Oseen vortex and which are often used to characterize short-wave instabilities, are poorly representative of real wake vortices.

Jacquín, L., Fabre, D., Geffroy, P. and Coustols, E.

"THE PROPERTIES OF A TRANSPORT AIRCRAFT WAKE IN THE EXTENDED NEAR FIELD: AN EXPERIMENTAL STUDY"

AIAA Paper No. 2001-1038, Reno, NV, January 2001

An experimental study on the formation and development of the vortex wake behind a small-scale transport aircraft model is presented. The data comprises LDV and hot wire measurements including two-point correlations. Steady and unsteady properties of the wake have been characterized for two cases, a high lift, and a clean configuration of the model. The analysis particularly focuses on the

unsteady properties of the vortices which are subjected to meandering. The discussion addresses elements that contribute to a better understanding of this phenomenon.

Jacquín, L., Fabre, D., Sipp, D. and Coustols, E.

"UNSTEADINESS, INSTABILITY AND TURBULENCE IN TRAILING VORTICES"

C. R. Physique, Vol. 6, 2005, pp. 399-41.

This paper is a review on the dynamics of vortices in fluids which get involved in aircraft wakes. Basic notions useful to appraise their dynamics are: inertial waves, 3D instabilities due to vortex interaction, vortex merging, vortex breakdown and turbulence. Each one of these topics is illustrated by means of experimental or numerical results.

Jacquín, L., Fabre, D., Sipp, D., Theofilis, V. and Vollmers, H.

"INSTABILITY AND UNSTEADINESS OF AIRCRAFT WAKE VORTICES"

Aerospace Science and Technology, Vol. 7, 2003, pp. 577-593.

This paper presents a review of theoretical and experimental results on stability and other unsteady properties of aircraft wakes. The basic mechanisms responsible for the propagation and the amplification of perturbation along vortices, namely the Kelvin waves and the cooperative instabilities, are first detailed. These two generic unsteady mechanisms are described by considering asymptotic linear stability analysis of model flows such as vortex filaments or Lamb-Oseen vortices. Extension of the linear analysis to more representative flows, using a bi-global stability approach, is also described. Experimental results obtained using LDV, hot wire and PIV in wind tunnels are presented and they are commented in the light of theory.

Jacquín, L., Fabre, D., Sipp, D., Theofilis, V. and Vollmers, H.

"INSTABILITY AND UNSTEADINESS OF AIRCRAFT WAKE VORTICES"

Proceedings 3rd ONERA-DLR Aerospace Symposium, Paris, France, June 2001, pp. S2-2/1-17

This paper presents a review of theoretical and experimental results on stability and other unsteady properties of aircraft wakes. Theory mainly concerns the dynamics of two-dimensional vortices. The basic mechanisms responsible for the propagation and the amplification of perturbation along vortices, namely the Kelvin waves and co-operative instabilities, are first detailed. These two generic unsteady mechanisms are described by considering asymptotic linear stability analysis of model flows such as vortex filaments or Lamb-Oseen vortices. Extension of the linear analysis to more representative flows, using a global stability approach, is also described. Experimental results obtained using LDV, hot wire and PIV in wind tunnels are presented and they are commented in the light of theory.

Jacquín, L., Molton, P., Loiret, P. and Coustols, E.

"AN EXPERIMENT ON JET-WAKE VORTEX INTERACTION"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

This experiment aims at providing original data on the interaction of propulsion jets with the wake vortices produced by a loaded wing. Considering that the jets of an aircraft interfere with the formation of its wake and the latter partly determine the dispersion of the jet exhausts, the present experiment is useful for two different types of aeronautical applications, namely the minimization of aircraft wake hazard and aircraft pollution (dispersion of pollutant, formation of contrails). The present experiment was launched to provide CFD teams with a representative data base for these two problems. The experimental device consists of a vortex generator and a hot jet generator. The vortex generator is a NACA 012 wing profile with a chord 125 mm and span 500 mm, suspended on a mast having a NACA 015 profile of chord 45 mm. The wing is positioned in the center of the test section, 750 mm downstream of the inlet section. The setup is stabilized by shrouds. The jet generator consists of two ejectors, 10 mm in diameter, on the pressure side of the airfoil, the jet being supplied with heated air. By changing the wing incidence, the thrust and temperature of the jets, different cases representative of different flight conditions could be simulated. The present paper focuses on the cruise regime and on the impact of the jet-vortex spacing. The effects of the jet temperature are also considered. Three positions of the jet-vortex spacing and two density ratios have been tested. The data base comprises surface flow visualizations, laser tomoscopies, thermocouple measurements, 3D laser velocimetry and hot wire probe measurements. The flow field measurements were conducted downstream of the wing between the wing trailing edge and 8 wingspans. The main conclusions of the study are (i) almost no effect of the jets on the vortex formation and dynamics when considering parameters representative of different flight regimes, and (ii) strong impact of the vortices on the jet dispersion, the interaction leading to different patterns when changing the jet-vortex spacing.

Jacquín, L., Molton, P., Loiret, P. and Coustols, E.

"AN EXPERIMENT ON JET-WAKE VORTEX INTERACTION"

AIAA Paper No. 2007-4363, Miami, FL, June 2007

The flow field produced by the interaction of two heated jets with the wake vortices of a rectangular wing is investigated in a research-type wind tunnel using an experimental set up producing conditions representative of an aircraft in cruise flight. The flow is characterized using a 3D-LDV system and thermocouples. Different spacing distances between the jets and the wing tips are considered. The temperature of the jets is also varying. In general, velocity and temperature contours reveal that the impact of the jets on the vortex properties remains small. Slight variations in the final vortex positions are observed when the jet/vortex spacing is changed due to slight modifications of the spanwise distribution of the vorticity due to the jets. Also, the statistics of the velocity fluctuations reveal that the jet turbulence promotes vortex meandering, probably through transient growth mechanisms. In most of the cases, the jet plume is wrapped around the vortices without penetrating significantly into

the cores. However, when the case jet/vortex spacing becomes small, one observes that the jets are quickly trapped into the vortices where they remain confined afterwards. As for the temperature effect, they are found to be almost negligible.

Jadic, I.

"ON AN EXTENSION OF THE KUTTA-JOUKOWSKI THEOREM TO THE SUPERSONIC REGIME"

Review Romanian Science and Technology, Vol. 24, No. 6, 1989, pp. 603-609.

In the present paper a formula is presented that enables the direct calculation of the force generated upon an infinite vortex line by a uniform supersonic flow (i.e., the equivalent of the Kutta-Joukowski theorem for subsonic flows). The methods dealing with vortex modelling of steady supersonic flows around wings make use of the small perturbation assumptions. It is shown that in the case of finite strength vortex line the induced velocity tends to infinity in the wave front and is zero elsewhere, infringing the perfect fluid hypothesis.

Jadic, I.

"AERODYNAMIC CALCULATION OF TANDEM WINGS IN SUPERSONIC FLOW BY MEANS OF SLLT"

Review Romanian Science and Technology, Vol. 35, July-August 1990, pp. 309-324.

This paper is part of a series dealing with the use of a lifting line type theory for the aerodynamic analysis of wings in supersonic flow, based upon small perturbation assumptions. The supersonic lifting line theory (LSST) makes use of a constant distribution of circulation along the chord, ensuring proper agreement with supersonic linearized flow theory for wings of large aspect ratio. The control point location resulted at 100 percent of the chord, from the condition of small aspect ratio wings to agree with Jones theoretical results. The analysis of errors involved with the SLLT approximation leads to the improved lifting line theory. In the present paper this improved theory is used for the calculation of wing-tail interference. As opposed to the the lifting line theories developed by Mirels and Haefeli, Martin and others, the loading on the wing is calculated by the lifting line procedure itself. The results presented herein show that the accuracy of the method is consistent with the linearized theory, enabling the estimation of downwash with a moderate computational effort.

Jadic, I.

"ON THE IMPROVEMENT OF THE SUPERSONIC LIFTING LINE THEORY"

Review Romanian Science and Technology, Vol. 35, March-April 1990, pp. 75-88.

In a previous paper a lifting line type theory for supersonic linearized flows (SSLT) has been defined. A prescribed (constant) distribution of bound vortices was assumed along the chord, ensuring proper agreement with 2-D supersonic flow theory for wings of large aspect ratio. The control point location has been determined by assuming that for wings with small aspect ratios, SLLT must agree with Jones'

theoretical results. It resulted that the control point must be placed at 100 percent of the chord, i.e. at the trailing edge. In the present paper two kinds of errors that affect the above-mentioned theory are discussed. The first error, due to the assumption of constant chord distribution of vortices, may be overcome by correlating the control point position with the aspect ratio. The second error is due to the possibility of information transfer beyond the inverse Mach cone limit. In order to cope with this, simple control flow solutions are used whenever possible. The resulting improved lifting line theory (SLLT + C) is ascertained by means of several comparisons with existing theoretical and experimental data. The correlation with these data is good, proving the accuracy gain of the method.

Jadic, I.

"WING CALCULATION IN SUPERSONIC FLOW BY MEANS OF THE SUPERSONIC LIFTING LINE THEORY"

Review Romanian Science and Technology, Vol. 35, May-June 1990, pp. 197-208.

A lifting line theory for supersonic linearized flows (SLLT) has been previously discussed in several papers. In the present paper the comparison of the improved supersonic lifting line theory (SLLT + C) with existing theoretical and experimental data is continued. The analysis covers the cases of straight, triangular, and swept isolated wings. The correlation with the test data is good, proving the accuracy of the method for usual planforms.

Jadic, I. and Constantinescu, V. N.

"LIFTING LINE THEORY FOR SUPERSONIC FLOW APPLICATIONS"

AIAA Journal, Vol. 31, No. 6, June 1993, pp. 987-994.

This paper is devoted to the study of a supersonic lifting line theory intended to provide both a means of aerodynamic calculation and a benchmark for the validation of the control point position for the related constant pressure panel methods. The model is based on the small perturbation assumption. A constant distribution of bound vortices is assumed along the chord whereas the spanwise load distribution is calculated by means of trigonometrical series, formally like the subsonic methods. The calculated aerodynamic coefficients are in good agreement with the reference data, the precision being compatible with the small perturbation assumption. The control panel position obtained is shown to vary as a function of aspect ratio from 100 to 88 percent of the local chord.

Jain, A. C.

"NUMERICAL SOLUTIONS OF NAVIER-STOKES EQUATIONS FOR THE STRUCTURE OF A TRAILING VORTEX"

NASA TM X-73361, January 1977, NASA Marshall Space Flight Center, Huntsville, AL

An attempt is made to understand the structure and decay of a trailing vortex through the numerical solutions of the full Navier-Stokes equations. Unsteady forms of the governing equations are recast in

terms of circulation, vorticity, and stream function as dependent variables, and a second upwind finite-difference scheme is used to integrate them with prescribed initial and boundary conditions. A discussion of the boundary conditions at the outer edge and at the outflow section of the trailing vortex is included. Different models of the flow are postulated, and solutions are obtained describing the development of the flow as integration proceeds in time. A parametric study is undertaken with a view to understand the various phenomena that may possibly occur in the trailing vortex. Using the Hoffman and Joubert law of circulation at the inflow section, the results of the present investigation are compared with the experimental data of Chigier and Corsiglia on a Convair-990 wing model and a rectangular wing. With an exponentially decaying law of circulation at the inflow section and an adverse pressure gradient at the outer edge of the trailing vortex, solutions depict vortex bursting through the sudden expansion of the core and/or through the stagnation and consequent reversal of the flow on the axis. It is found that this bursting takes place at lower values of the swirl ratio as the Reynolds number increases.

Jain, R.

"HOVER PREDICTIONS ON THE S-76 ROTOR WITH TIP SHAPE VARIATION USING HELIOS"

Journal of Aircraft, Vol. 55, No. 1, January-February 2018, pp. 66-77.

High-resolution, time-accurate computational fluid dynamics validation of a 9.34 ft, four-blade, Mach-scaled S-76 rotor in hover is performed using the U.S. Department of Defense Computational Research and Engineering Acquisition Tools and Environments -- Air Vehicles Helios software. The effect of blade tip shape variation is studied for three tip shapes: rectangular, swept tapered, and swept tapered anhedral. The effect of tip Mach number is studied for the swept-tapered tip. Computed results include rotor performance, blade air loads, and tip-vortex strength and position. The performance predictions are compared against the test measurements and good agreement is obtained. Compared with the swept-tapered tip, the rectangular blade incurs compressibility losses near the tip. The addition of anhedral to the swept-tapered tip improves performance as a result of redistribution of thrust.

Jain, R.

"SENSITIVITY STUDY OF HIGH-FIDELITY HOVER PREDICTIONS ON THE SIKORSKY S-76 ROTOR"

Journal of Aircraft, Vol. 55, No. 1, January-February 2018, pp. 78-88.

Hover performance calculations are performed for a 9.34 ft, four-blade, Mach-scaled, S-76 rotor with an anhedral tip using different computational-fluid-dynamics approaches to assess the variability in prediction. Time-accurate Navier-Stokes calculations are performed using the High Performance Computing Modernization Program Computational Research and Engineering Acquisition Tool and Environment Air Vehicles Helios software suite with OVERFLOW and FUN3D as near-body solvers, and the standalone OVERFLOW solver. Different modeling options exercised include structured and unstructured meshes for the blades, adaptive mesh refinement in the blade mesh, adaptive mesh

refinement in the wake mesh, and inviscid and detached-eddy simulation modeling in the wake. Rotor performance, blade air loads, and wake geometry from the different calculations show consistent predictions. The agreement between computed figure of merit and test data is good at high-thrust conditions but only fair at lower thrust.

Jain, R. and Conlisk, A. T.

"INTERACTIONS BETWEEN TIP-VORTICES IN ROTOR WAKES"

American Physical Society, 50th Annual Meeting Division of Fluid Mechanics, Nov. 1998, Philadelphia, PA,

In recent experiments, it was observed that the tip vortices shed from a two-bladed rotor can interact significantly. The interaction consists of a turn of the tip-vortex from one blade rolling around a turn of the tip-vortex from the other blade. Visualized in a planar light sheet, the two vortices spiral around each other prior to merging into a single vortex. Moreover, the wake does not contract monotonically as often depicted but expands as one of the vortices moves radially outward due to the interaction. This behavior is illustrated by the numerical calculation of the motion of a pair of ring vortices. It is observed that the pair of rings, placed initially parallel and of the same strength roll around each other, by alternate contraction and expansion of the ring radius. Numerical calculations show that the ring interaction is complicated when the rings are initially inclined. Numerical solutions for a two-bladed rotor in hover and descent are presented. A lifting-line theory is used to model each rotor blade and a fully unsteady computation of the motion of the tip-vortices is carried out using a highly accurate Adams-Moulton method to advance the vortices. The modified Biot-Savart law is used to describe the vortex structure. This type of interaction in the wake contradicts many of the current computational results which consider the wake to be spatially periodic.

Jain, R., Conlisk, A. T., Mahalingam, R. and Komerath, N. M.

"INTERACTION OF TIP-VORTICES IN THE WAKE OF A TWO-BLADED ROTOR"

Proceedings 54th Annual Forum of the American Helicopter Society, May 1998, Washington DC.

In recent experiments, it was observed that the tip vortices shed from a two-bladed rotor can interact significantly. The interaction consists of a turn of the tip-vortex from one blade rolling around a turn of the tip-vortex from the other blade. Visualized in a planar light sheet, the two vortices spiral around each other prior to merging into a single vortex. One complete cycle of the roll-up process takes about one and a half rotor cycles. The wake does not contract monotonically but expands as one of the vortices moves radially outward due to the roll-up. This behavior is illustrated by the numerical calculation of the motion of a pair of ring vortices. It is observed that the pair of rings, placed initially parallel and of the same strength roll around each other, by alternate contraction and expansion of the ring radius. Numerical calculations show that the ring interaction is complicated when the rings are initially inclined. Next the case of a two-bladed rotor is considered. A lifting-line theory is used to model each rotor blade and a fully unsteady computation of the motion of the tip-vortices is carried out using

a highly accurate Adams-Moulton method to advance the vortices. The modified Biot-Savart law is used to describe the vortex structure. It is shown that the tip-vortex interaction is periodic and deterministic.

James, M. and Brown, J.

"NATIONAL AIR TRAFFIC RULE CHANGE 7110.308, WAKE TURBULENCE WITH CLOSELY SPACED PARALLEL RUNWAYS"

AIAA Paper No. 2010-9166, September 2010, Fort Worth, TX.

The goal of this paper is to present the findings from two studies that modeled the Wake Turbulence Program's National Air Traffic Rule Change 7110.308 at approved airports. Rule Change 7110.308 allows approved airports to operate with parallel approach runways in Instrument Meteorological Conditions, which previously would operate as a single arrival stream runway. The purpose of this study was to show the benefits of Rule Change 7110.308 to gain strong facility support of the procedure. Multiple scenarios were modeled for the newly developed National Rule Change 7110.308 at two airports, Seattle-Tacoma and Newark Liberty International Airports. These are two very different airports yet the rule change has the potential to provide benefits regardless of the differences. The paper thoroughly explains National Rule Change 7110.308, the methodology used to quantify the potential benefits, how the rule would be used at Seattle-Tacoma and Newark Liberty International Airports and concludes with the modeling results for each airport.

Jameson, A. R. and Kostinski, A. B.

"PARTIALLY COHERENT BACKSCATTER IN RADAR OBSERVATIONS OF PRECIPITATION"

Journal of the Atmospheric Sciences, Vol. 67, 2010, pp. 1928-1946.

Classical radar theory only considers incoherent backscatter from precipitation. Can precipitation generate coherent scatter as well? Until now, the accepted answer has been no, because hydrometeors are distributed sparsely in space (relative to radar wavelengths) so that the continuum assumption used to explain coherent scatter in clear air and clouds does not hold. In this work, a theory for a different mechanism is presented. The apparent existence of the proposed mechanism is then illustrated in both rain and snow. A new power spectrum $Z(f)$, the Fourier transform of the time series of the radar backscattered reflectivity, reveals statistically significant frequencies f of periodic components that cannot be ascribed to incoherent scatter. It is shown that removing those significant f s from $Z(f)$ at lower frequencies greatly reduces the temporal coherency. These lower frequencies, then, are associated with the increased temporal coherency. It is also shown that these f s are also directly linked to the Doppler spectral peaks through integer multiples of one-half the radar wavelength, characteristic of Bragg scatter. Thus, the enhanced temporal coherency is directly related to the presence of coherent scatter in agreement with theory. Moreover, the normalized backscattered power spectrum $Z(f)$ permits the estimation of the fractional coherent power contribution to the total power, even for an incoherent radar. Analyses of approximately 26,000 one-second $Z(f)$ in both rain and snow reveal that the coherent scatter is pervasive in these data. These findings present a challenge to the

usual assumption that the scatter of radar waves from precipitation is always incoherent and to interpretations of backscattered power based on this assumption.

Janic, M.

"TOWARD TIME-BASED SEPARATION RULES FOR LANDING AIRCRAFT"

Transportation Research Record, Issue No. 2052, 2008, pp. 79-89.

Aircraft landing on the same runway are potentially exposed to a similar wake vortex hazard, under either instrument meteorological conditions (IMC) or visual meteorological conditions (VMC) when the air traffic control (ATC) distance-based instrument flight rules (IFR) and visual flight rules (VFR) are applied, respectively. Since IFR are stricter than VFR, the runway landing capacity is lower under IMC than under VMC. Possibilities are investigated for introducing time-based ATC separation rules instead of the current distance-based ATC separation rules between landing aircraft as an option for increasing the runway landing capacity under IMC and consequently decreasing the existing gap between IFR and VFR capacity. A model for calculating the landing capacity of a single runway on the basis of ATC time-based separation rules was developed. In addition to these rules, which would be set up by using the current ATC distance-based separation rules and the advanced knowledge on the current and predicted behavior of the wake vortex influenced by the weather conditions, the model uses other inputs, such as the structure of fleet mix in terms of the proportion of particular aircraft categories, which are represented by their wake vortex parameters (the approach speed, wingspan, and weight), and the geometry of the approach corridor, which enables landing on a given runway. The model output is the matrix of the standardized time-based separation rules for different combinations of landing aircraft sequences, which would be applicable to both VMC and IMC, and the runway landing capacity calculated for combinations of the time-based separation rules depending on the current and predicted wake vortex characteristics and behavior. The model is applied to calculating the landing capacity of a single airport runway.

Janic, M.

"STEEPER APPROACH PROCEDURE FOR INCREASING ULTIMATE CAPACITY OF CLOSELY SPACED PARALLEL RUNWAYS"

Transportation Research Record, 2007, pp. 81-89

The steeper approach procedure (SAP) is investigated as an innovative option for increasing the ultimate arrival capacity of closely spaced parallel runways under instrument meteorological conditions and instrument flight rules. SAP is based on the two pairs of instrumented landing systems, each enabling the certified aircraft to approach a given parallel runway at either the standard (3 deg) or steeper (5 to 7 deg) glide slope (GS) angle. The difference in the GS angles allows application of the ATC vertical separation rules between the arriving aircraft; this can mitigate the impact of wake vortices on the aircraft in trail separation while on the same or different approach trajectories. A combination of

these with the ATC longitudinal and horizontal-diagonal separation rules has the potential to increase the ultimate arrival capacity of closely spaced parallel runways. An analytical model was developed for calculating the arrival ultimate capacity of closely spaced parallel runways.

Janic, M.

"MODEL OF ULTIMATE CAPACITY OF DUAL-DEPENDENT PARALLEL RUNWAYS"

Transportation Research Record, Issue 1951, 2006, pp. 76-85

This paper develops an analytical model of the ultimate capacity of dual-dependent parallel runways (with close or intermediate spacing), where ultimate capacity is defined as the maximum number of aircraft accommodated during a given period (usually 1 h or 15 min) under constant demand for service and other given conditions. The model uses six inputs: geometry (configuration) of parallel runways; air traffic control (ATC) separation rules; technologies for aircraft primary navigation, communication, and air traffic surveillance, which influence separation rules and the degree of dependency of two runways; aircraft fleet mix in terms of wake vortex categories and approach and departure speeds; proportion of arrival and departure demand; and ATC tactics of sequencing particular aircraft types and operations. The output represents the so-called capacity coverage curve, which reflects different scenarios of using given runways. The model is used to calculate the capacity of a large European airport.

Jankun-Kelly, M., Jiang, M., Thompson, D. and Machiraju, R.

"VORTEX VISUALIZATION FOR PRACTICAL ENGINEERING APPLICATIONS"

IEEE Transactions on Visualization and Computer Graphics, Vol. 12, No. 5, September-October 2006, pp. 957-964.

In order to understand complex vortical flows in large data sets, we must be able to detect and visualize vortices in an automated fashion. In this paper, we present a feature-based vortex detection and visualization technique that is appropriate for large computational fluid dynamics data sets computed on unstructured meshes. In particular, we focus on the application of this technique to visualization of the flow over a serrated wing and the flow field around a spinning missile with dithering canards. We have developed a core line extraction technique based on the observation that vortex cores coincide with local extrema in certain scalar fields. We also have developed a novel technique to handle complex vortex topology that is based on k-means clustering. These techniques facilitate visualization of vortices in simulation data that may not be optimally resolved or sampled. Results are included that highlight the strengths and weaknesses of our approach. We conclude by describing how our approach can be improved to enhance robustness and expand its range of applicability.

Janota, P., Coburn, A. R., Thokar, G. A. and Osovski, L.

"RELATIONSHIPS BETWEEN WAKE VORTEX DECAY AND ATMOSPHERIC VARIABLES"

Proceedings Sixth Conf. on Aviation Weather Systems, American Meteorological Society, Dallas, TX, January 1995, pp. 161-165

An attempt is made to relate the lifetimes and descent distances of aircraft wake vortices to measured and derived aircraft and atmospheric variables. The primary analytical method used is linear regression. The main objective is to look for physical relationships; a secondary objective is to determine the validity of predicting vortex behavior from independent data using the regression formula. Preliminary results support the observation that vortex lifetimes are shortened due to turbulence as daytime heating increases. The prediction that strong stability would also reduce lifetimes was not observed.

Janus, J. M. and Chatterjee, A.

"USE OF A WAKE-INTEGRAL METHOD FOR COMPUTATIONAL DRAG ANALYSIS"

AIAA Journal, Vol. 34, No. 1, January 1996, pp. 188-190.

The capacity to predict drag due to lift using numerical simulations of the flow field and a wake-integral approach has been studied. An important finding during this research was the presence of low-level spurious vorticity in the flow. Future work must address the problem of requiring arbitrary filters to determine the extent of the vortical wake that ultimately governs the integral limits. Since the postprocessor uses a wake-based approach to compute the lift and drag about a lifting body, it was found that to correctly predict these force components it is necessary to very accurately resolve the flow field in this region. An accurate resolution of the vortical field is critical when using the present approach for induced drag calculations. To maintain the performance of this approach, a sufficiently dense mesh is required in the wake region. This yields somewhat of a tradeoff situation since the errors associated with surface pressure integration can also be reduced with a sufficient increase in mesh density local to the body. Perhaps the use of a computational method specifically designed for the unmolested transport of vorticity would be the ultimate complement to the wake-integral method.

Jardin, M. and Mueller, E.

"OPTIMIZED MEASUREMENTS OF UAV MASS MOMENT OF INERTIA WITH A BIFILAR PENDULUM"

AIAA Paper 2007-6822, August 2007, Hilton Head, SC.

A bifilar (two-wire) pendulum is a torsional pendulum consisting of a test object suspended by two thin parallel wires. The pendulum oscillates about the vertical axis. The restoring torque of the bifilar pendulum is provided by the gravitational force as rotations from the rest state cause the test object to raise slightly. The mass moment of inertia is computed using dynamic modeling, measurements of the oscillation period, and the physical dimensions of the bifilar pendulum such as the length and separation displacement of the pendulum wires. A simulation technique is described that improves estimates of the mass moment of inertia by considering the nonlinear effects of damping and large angular displacements. An analysis of the error variance of mass moment of inertia measurements is also described. The resulting expression for the error variance is used to optimize the physical

parameters of the bifilar pendulum to obtain the moment of inertia measurement with the minimum error variance. Monte Carlo simulations were used to validate the parameter optimization technique. Experimental results are presented for a uniform-density test object for which the moment of inertia is straightforward to compute from geometric considerations. Results are also presented for a small unmanned air vehicle, which was the intended application for this moment of inertia measurement technique.

Jardin, M. R. and Mueller, E. R.

"OPTIMIZED MEASUREMENTS OF UNMANNED-AIR-VEHICLE MASS MOMENT OF INERTIA WITH A BIFILAR PENDULUM"

Journal of Aircraft, Vol. 46, No. 3, May-June 2009, pp. 763-775.

A bifilar (two-wire) pendulum is a torsional pendulum consisting of a test object suspended by two thin parallel wires. The pendulum oscillates about the vertical axis. The restoring torque of the bifilar pendulum is provided by the gravitational force as rotations from the rest state cause the test object to raise slightly. The mass moment of inertia is computed using dynamic modeling, measurements of the oscillation period, and the physical dimensions of the bifilar pendulum such as the length and separation displacement of the pendulum wires. A simulation technique is described that improves estimates of the mass moment of inertia by considering the nonlinear effects of damping and large angular displacements. An analysis of the error variance of mass moment of inertia measurements is also described. The resulting expression for the error variance is used to optimize the physical parameters of the bifilar pendulum to obtain the moment of inertia measurement with the minimum error variance. Monte Carlo simulations were used to validate the parameter optimization technique. Experimental results are presented for a uniform-density test object for which the moment of inertia is straightforward to compute from geometric considerations. Results are also presented for a small unmanned air vehicle, which was the intended application for this moment of inertia measurement technique.

Jarvinen, P. O.

"AIRCRAFT WING-TIP VORTEX MODIFICATION"

Journal of Aircraft, Vol. 10, No. 1, January 1973, pp. 63-64

The results of a low-speed experimental wind tunnel study of the modification of a wing tip vortex using a tip mounted, upstream facing jet are discussed. The tests were performed in the MIT Wright Brothers 7 ft by 10 ft closed return subsonic wind tunnel. The vorticity of the vortex was measured by a vorticity meter located seven chord lengths downstream of the wing trailing edge and in line with the wing tip. A moveable smoke generator unit was used to obtain flow visualization photographs. It was found that the upstream facing jet is more effective in reducing the vorticity at the same value of the jet momentum coefficient (essentially a thrust coefficient) than the downstream facing jet.

Jasion, G. and Shrimpton, J.

"PREDICTION OF BROWNOUT INCEPTION BENEATH A FULL-SCALE HELICOPTER DOWNWASH"

Journal of the American Helicopter Society, Vol. 57, 2012, pp. 042006-1 to 042006-13.

Dust entrained by low flying helicopters leads to the degraded visual environment, brownout. Particle inception is a critical stage in the development of the dust cloud. Here, near-wall Lagrangian particle forces are considered through analyzing an approximate time-averaged full-scale rotor flow. This simplified flow does not attempt to predict brownout, instead it provides scales and velocity data in the near-wall region, compares the role of particle-fluid forces, and provides a foundation for Lagrangian entrainment models. The analysis shows that three characteristic particle sizes are exposed to different physics in different boundary layer zones, a function of the distance from the helicopter. Drag is the dominant aerodynamic force, cohesion is large for small particles, but wall-bounded lift is sufficient to entrain medium-sized particles. A complementary analytical prediction of tip vortices found that both large-scale inviscid features and small-scale viscous features of the boundary layer are significant.

Jategaonkar, R., Fischenberg, D. and von Gruenhagen, W.

"AERODYNAMIC MODELING AND SYSTEM IDENTIFICATION FROM FLIGHT DATA -- RECENT APPLICATIONS AT DLR"

Journal of Aircraft, Vol. 41, No. 4, July-August 2004, pp. 681-691

This paper provides an overview of a few selected system-identification activities carried out during the last decade at DLR, the German Aerospace Center. After a brief account of parameter-estimation methods and of consistency checking of recorded flight data, an emphasis is placed on 1) development of global, high-fidelity aerodynamic databases for training simulators; 2) models for in-flight simulator; 3) modeling of stall hysteresis; 4) estimation of aerodynamic flowfield characteristics and validation of aircraft reaction models from wake vortex encounter flights; and 5) a parametric wake distortion model to improve helicopter coupling off-axis response. These examples cover a variety of flight vehicles with widely different characteristics, namely, the military transport aircraft Transall C-160, commuter aircraft Dornier 328, in-flight simulator VFW-614 ATTAS, high-altitude research aircraft G850 Strato 2C, Airbus-type aircraft, fly-by-wire helicopter BO-105, and fly-by-light helicopter EC-135. Besides parameter estimation aspects, those related to model validation are discussed. Through succinct examples it is brought out that system identification has become an indispensable tool to support not only research but also industry activities in various key areas such as model validation, handling qualities evaluation, control law design, and flight-vehicle design and certification. Thus, it contributes significantly to risk and cost reduction.

Jayaraman, B. and Potsdam, M.

"EFFECT OF FUSELAGE AND WIND TUNNEL WALL ON FULL-SCALE UH-60A ROTOR TIP VORTEX PREDICTION"

AIAA Paper 2016-3131, June 2016, Washington, DC.

An investigation of the effect of the fuselage and the wind tunnel wall on the prediction of rotor tip vortices is carried out for the full scale UH-60A rotor in the 40- by 80-foot National Full-Scale Aerodynamic Complex (NFAC) wind tunnel. A coupled Computational Fluid Dynamics (CFD) and Computational Structured Dynamics (CSD) simulation is carried out using the US Army and HPCMP CREATE-AV [TM] Helios flow solver. The rotor blades are modeled using structured grids and the NFAC Large Rotor Test Apparatus (LRTA) fuselage is modeled using an unstructured grid. OVERFLOW is used for the structured grids and FUN3D is used for the unstructured grids. A higher order adaptive Cartesian solver is used in the off-body to model the rotor tip vortices. Helios predictions for the isolated rotor and rotor-fuselage configurations in free air and wind tunnel are compared to the reprocessed PIV data for the low-speed descending flight condition (rotor advance ratio = 0.15). Overall, the vortex properties (core radius, circulation, and location) predicted by Helios are in good agreement with the data. Inclusion of wind tunnel walls significantly improved the vortex trajectory predictions, particularly in the later delayed azimuth locations, resulting in a close agreement with measured data. Inclusion of the LRTA fuselage changed the blade loading characteristics that lead to weaker circulation prediction compared to the isolated rotor case. No significant differences were noticed in the prediction of core radius. Rotor wake and vortex properties, but not vortex location, can be predicted with reasonable accuracy using the isolated rotor model in free air with corrected shaft angle.

Jayavel, S., Patil, P. P. and Tiwari, S.

"INTERACTION OF A SKEWED RANKINE VORTEX PAIR"

Physics of Fluids, Vol. 20, 2008, pp. 083601-1 - 083601-9

An analytical investigation is carried out to study the kinematics of a fluid particle in an interacting field of a skewed pair of fixed Rankine vortices. A general formulation governing the kinematics of a fluid particle has been presented based on the superposition of the velocity field due to each vortex in the pair. The kinematics of a Lagrangian fluid particle is found to be governed by a nonlinear dynamical system. The fixed or stationary points of the dynamical system have been identified analytically and their existence is confirmed by the nature of particle paths in the neighborhood of fixed points. The nature of the particle path and velocity signal is reported for general as well as special configurations of the vortex pair in the presence and absence of an external uniform flow. As a specific application of the proposed problem, superposition of the translational velocity on a semi-infinite field of longitudinal vortices generated by vortex generators mounted on fin plates of heat exchangers has also been studied.

Jaynes, D. W., Manwell, J. F., McGowan, J. G., Stein, W. M. and Rogers, A. L.

"MTC FINAL PROGRESS REPORT: LIDAR"

Final Report, July 2007, Renewal Energy Research Laboratory, University of Massachusetts, Amherst, MA.

This report gives a detailed description of the fundamental principles that govern the operation of laser remote sensing devices. This report also outlines a process by which a specific laser anemometer is validated with respect to cup anemometry. The data validation experiment summarizes approximately 1.5 months of concurrent laser anemometer and cup anemometer wind speed data. The validation experiment concludes that the laser anemometer can achieve correlation of 0.978, 0.984 and 0.984 at 118m, 87m and 61m respectively when compared to in-situ cup anemometry. The operation of the laser anemometer is subject to certain difficulties such as power failure but its advantages over cup anemometer-based wind speed measurement are significant. The advantages in laser remote sensing over traditional cup anemometers are explored in a comprehensive uncertainty analysis of the two sensor types. The laser anemometer is found to exhibit approximately 5.2% overall wind speed measurement error while the NRG cup anemometers exhibit approximately 8.3% overall wind speed measurement error. The wind resource characteristics in Hull, Massachusetts are also characterized and the six-month average wind speed was found to be 7.27 m/s at a height of 118m while the average shear exponent, α , is found to be 0.19. Based on these results, it can be concluded that the laser anemometer used in the data validation experiment is acceptable for use in wind resource assessment applications.

Jeanmart, H. and Winckelmans, G. S.

"VLES OF AIRCRAFT WAKE VORTICES IN A TURBULENT ATMOSPHERE: A STUDY OF DECAY"

Advances in LES of Complex Flows, Fluid Mechanics and Its Applications, Vol. 65, 2004, pp. 311-326.

Very Large-Eddy Simulations (VLES) of aircraft wake vortices in various atmospheric turbulence conditions are carried out. The turbulence level is characterized by the eddy dissipation rate and ranges from very strong to weak. The turbulence is assumed isotropic. Two LES models are considered. Most simulations were done using explicit gaussian filtering and a mixed model: the tensor-diffusivity model supplemented by a dynamic Smagorinsky term. As a point of comparison, some simulations were done using the classical dynamic Smagorinsky model alone (thus without explicit filtering). Initially, the wake vortices are assumed to follow the fairly 'universal' circulation profile shortly after rollup. The vortex global circulation is investigated: its decay exhibits a similar behavior in all cases, leading to the exponential decay model based on the eddy dissipation rate. The present model differs from others by the presence of a time delay before the exponential decay. The constant defining the decay rate is also found to be quite different from that found in the literature. This lack of agreement is partially explained by the differences in the definitions of circulations.

Jeansmart, H. and Winckelmans, G. S.

"VLES OF AIRCRAFT WAKE VORTICES IN A TURBULENT ATMOSPHERE: A STUDY OF DECAY"

Proceedings of the EUROMECH Colloquium, No. 412 on Advances in LES of Complex Flows, Munich, Germany, October 4-6, 2000, pp. 311-326

Very Large-Eddy Simulations (VLES) of aircraft wake vortices in various atmospheric turbulence conditions are carried out. The turbulence level is characterized by the eddy dissipation rate and ranges from very strong to weak. The turbulence is assumed isotropic. Two LES models are considered. Most simulations were done using explicit gaussian filtering and a mixed model: the tensor-diffusivity model supplemented by a dynamic Smagorinsky term. As a point of comparison, some simulations were done using the classical dynamic Smagorinsky model alone (thus without explicit filtering). Initially, the wake vortices are assumed to follow the fairly 'universal' circulation profile shortly after rollup. The vortex global circulation is investigated: its decay exhibits a similar behavior in all cases, leading to the exponential decay model based on the eddy dissipation rate. The present model differs from others by the presence of a time delay before the exponential decay. The constant defining the decay rate is also found to be quite different from that found in the literature. This lack of agreement is partially explained by the differences in the definitions of circulations.

Jeddi, B. G., Shortle, J. F. and Sherry, L.

"STATISTICS OF THE APPROACH PROCESS AT DETROIT METROPOLITAN WAYNE COUNTY AIRPORT"

Proceedings of the 2nd International Conference on Research in Air Transportation, 2006, Belgrade, Serbia and Montenegro.

Dealing with uncertainty is a necessary and difficult aspect in operations analysis of complex systems such as the air transportation system. We represent these uncertainties in the approach process by probability distributions. This paper provides statistical observations of the approach and landing process at Detroit Metropolitan airport (DTW) for one week of February 2003. These probability distributions are based on aircraft track record data at DTW which are collected by a multilateration surveillance system. After explaining characteristics of the database and its short comings, we present a methodology to extract necessary statistical samples. From this, we obtain appropriate probability distributions for landing time interval (LTI), inter arrival distance (IAD), and runway occupancy time (ROT) presented under instrument flight rules (IFR) and peak traffic periods.

Jeddi, B. G., Shortle, J. F. and Sherry, L.

"STATISTICAL SEPARATION STANDARDS FOR THE AIRCRAFT-APPROACH PROCESS"

IEEE/AIAA Proceedings, 25th Digital Avionic Systems Conf., October 2006, pp. 1-13

Demand for air transportation has been increasing. A response to this is enhancing the runway utilization and throughput before investing on new runways or instruments. Runway throughput can be increased by reducing in-trail landing separation between aircraft, but the consequence may be an increase in the change of a severe wake vortex encounter or a simultaneous runway occupancy (or go-around). Current instrument flight rule (IFR) standards provide fixed separation minima for given pairs of wake vortex weight classes of aircraft. In practice, the observed separation is a random variable and

fluctuates near or above the specified minimum. In this paper, we propose a framework for statistical separation standards that specifies not only a lower bound for the separation but also a standard for the target value and the variance of the process. We address the question of what a more efficient separation standard is to control the risk in the approach process. We address the question of what a more efficient separation standard is to control the risk in the approach process. We also consider whether separation variability may be reduced by employing such standards, i.e. more detailed standards that take the 'realized variability' into account. Analytical results of this study suggest that (under specific assumptions) throughput can be increased to some extent without degrading safety for the given facilities, infrastructure, and weather condition. The arguments and concepts are illustrated with statistical observations from Detroit airport (DTW).

Jeffery, R. W., Broadbent, E. G. and Hazell, A. F.

"WIND-TUNNEL INVESTIGATION OF VORTEX REFRACTION EFFECTS ON AIRCRAFT NOISE PROPAGATION"

Journal of Aircraft, Vol. 14, No. 8, August 1977, pp. 737-745

One possible method for reducing aircraft flyover noise is to site the engines so that the wing vortex can refract sound away from the ground. A series of experiments was carried out in the RAE 24-foot wind tunnel using a model of the HP 115 slender delta research aircraft, which produced a strong leading-edge vortex when set at incidence. The engine noise was simulated by a Hartmann whistle mounted above the engine intake. The results are compared with a theoretical prediction based on ray theory and a simplified representation of the wing vortex structure.

Jeffreys, H. B.

"SYSTEMS SIMULATION FOR AN AIRPORT TRAILING VORTEX WARNING SYSTEM"

NASA TM X-64704, October 1972, NASA Marshall Space Flight Center, Huntsville, AL

This report documents the approach, development, and limited system studies associated with a system simulation for an Airport Trailing Vortex Warning System (ATVWS). It attempts to show the usefulness of a systems engineering approach to the problem of developing a system, as dictated by aircraft vortices, which will increase air traffic flow in the takeoff/landing corridors of busy airports while maintaining the required safety factor, for each operation.

Jeffreys, H. B. and Bilbro, J. W.

"DEVELOPMENT OF A LASER DOPPLER SYSTEM FOR THE DETECTION AND MONITORING OF ATMOSPHERIC DISTURBANCES"

Electro-Optics '75 International Laser Conf., Anaheim, CA, November 1975

The Marshall Space Flight Center has developed a Scanning Laser Doppler System capable of detecting and monitoring atmospheric disturbances. This system has been used successfully to detect

and track wake vortices of landing aircraft and to obtain vertical wind profiles in the atmosphere. The laser system, which is installed in a mobile van, is a focused continuous wave, CO₂ system which determines the line-of-sight velocities of particles in the focal volume of the system by measuring the Doppler shift created by these particles. At present, the system has been designed to have a range coverage of approximately 2,000 feet with a vertical angle coverage of approximately 60 deg. The system can detect Doppler velocities of up to 200 feet/second with a velocity resolution of approximately 1.8 feet/second. A complete velocity profile is provided by the system at each point in space at which it is focused. This information is further processed to provide specific velocity information in regions of interest.

Jeffreys, H. B., Sonnenschein, C. M. and DiMarzio, C. A.

"PERFORMANCE OF A CO₂ LASER VORTEX DETECTION SYSTEM"

IEEE/OSA Conf. on Laser Engineering and Applications, Washington, DC, May 1975.

A scanning CO₂ laser Doppler velocimeter has been used to obtain transport and velocity characteristics of aircraft trailing vortices. System performance and vortex data are presented.

Jelalian, A. V., Keene, W. H., McDonagh, T., Seeber, K. N. and Sonnenschein, C. M.

"WAKE VORTEX LASER RADAR"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 41-1 - 41-18

Coherent laser radar systems have been utilized to remotely detect the motion of the atmosphere, by obtaining Doppler backscattering of the laser energy from aerosols naturally suspended in air. These activities were pioneered by Raytheon under contract to the NASA Marshall Space Flight Facility, when the first remote measurements of a CO₂ laser radar system were utilized to determine the atmospheric wind velocity, with a focused CO₂ laser system in 1967. In 1969, LIDAR was first used to remotely measure aircraft wake vortex motion. These coherent detection systems use the temporal and spatial coherence of a laser radar (LIDAR) to obtain Doppler backscattering from aerosols and particulate matter. These systems operate both in the near field and far field of the system.

Jelalian, A. V., Keene, W. H., Sonnenschein, C. M. and Huffaker, R. M.

"LASER DOPPLER SYSTEMS OF REMOTE ATMOSPHERIC MEASUREMENTS"

IEEE Northeast Electronics Research and Engineering Meeting, Boston, MA, November 1971

This paper discusses several field measurements that have been performed with a CO₂ laser Doppler homodyne system sampling the clear atmosphere for the remote measurement of atmospheric winds and aircraft wake vortices. This system makes use of the particulate matter normally present in the lower atmosphere to provide backscattering and to act as tracers of air motion.

Jenkins, B. Z. and Marks, A. S.

"ROTOR DOWNWASH VELOCITIES ABOUT THE UH-1M HELICOPTER - FLIGHT TEST MEASUREMENTS AND THEORETICAL CALCULATIONS"

RD-75-27, January 1975, U.S. Army Missile Command, Redstone Arsenal, Alabama

Downwash velocity data from a flight test of the UH-1M helicopter are presented in comparison with calculated values. Hot film anemometers were used to measure flow velocities at five points in the downwash for a variety of aircraft forward velocities and hover. The theoretical predictions were made using a mathematical model of sources and sinks to simulate the fuselage and vortex filaments to simulate the rotor wake.

Jenkins, M. W. M. and Hackett, J. E.

"A PILOT-IN-THE-LOOP, VISUAL SIMULATION OF TRAILING VORTEX ENCOUNTERS AT LOW SPEED"

AIAA Paper 1975-0104, Pasadena, CA, 197.

A fixed base, visual flight simulator, using a transport cab, was used to explore pilot-in-the-loop encounters of a C-130 type transport flying in the wake of a C-5A. Some 80 flight conditions were flown through a range of vortex strengths, core radii, spatial orientations, direction of rotation, and encounter altitudes. Vortex-lattice modeling techniques were used to update the forces and moments of the penetrating aircraft. It established the feasibility of digitally updating the encounter aerodynamics in real time to permit pilot-in-the-loop visual tasks to be performed. Suggested approaches to regulatory boundaries have been made.

Jenkins, M. W. M. and Meyer, R. T.

"VORTICAL WAKE HAZARD ADVISORY"

AFFDL-TR-76-146, February 1977, Lockheed-Georgia Co., Marietta, GA

The study reported herein was an analytical effort to define separation criteria for USAF aircraft during landing and taking-off. The approach used was a blend of theoretical and experimental work. Existing theoretical methods, analyses and data were used and the results were conditioned by published flight test and pilot-in-the-loop simulation data. Results from the study are presented as a suggested Interim Advisory for USAF operational aircraft when flying in the terminal area. In this advisory, the current operational fleet has been divided into four classes of vortex-generating and vortex-encountering aircraft. Specific separation recommendations are presented in the form of 'avoid volumes' of airspace for each combination of the generating and encountering aircraft. These 'avoid volumes' include the effects of aircraft relative speeds, flight paths, local winds and atmospheric conditions.

Jensen, R. J.

"EXPERIMENTAL STUDY OF FAR-FIELD WING WAKES"

M.S. Thesis, January 1973, Mass. Institute of Technology, Cambridge, MA

The results of a flow visualization experiment in the M.I.T. Ship Model Towing Tank show that sinusoidal instability and vortex breakdown in a lifting surface wake can be forced by differential flap oscillation. A theoretical investigation reveals the driving factors are displacement of the vortex from its mean position, sinusoidal variation of circulation along the trailers, and shed vorticity. Optimum wavelengths at which the sinusoidal instability goes to completion in minimum time are found and indicate that inclusion of the driving factors causes the optimum to diverge substantially from the locus of maximum growth rates as predicted by linear theory. Core axial velocities are also investigated and found to be high compared with previous research.

Jentink, H. W. and Bogue, R. K.

"OPTICAL AIR FLOW MEASUREMENTS FOR FLIGHT TESTS AND FLIGHT TESTING OPTICAL AIR FLOW METERS"

RTO-MP-SCI-162, 2005, Paper 11, Neuilly-sur-Seine, France

Optical air flow measurements can support the testing of aircraft and can be instrumental to in-flight investigations of the atmosphere or atmospheric phenomena. Furthermore, optical air flow meters potentially contribute as avionics systems to flight safety and as air data systems. The qualification of these instruments for the flight environment is where we encounter the systems in flight testing. An overview is presented of different optical air flow measurement techniques applied in flight and what can be achieved with the techniques for flight test purposes is reviewed. All in-flight optical airflow velocity measurements use light scattering. Light is scattered on both air molecules and aerosols entrained in the air. Basic principles of making optical measurements in flight, some basic optical concepts, electronic concepts, optoelectronic interfaces, and some atmospheric processes associated with natural aerosols are reviewed. Safety aspects in applying the technique are shortly addressed. The different applications of the technique are listed and some typical examples are presented. Recently NASA acquired new data on mountain rotors, mountain induced turbulence, with the ACLAIM system. Rotor position was identified using the lidar system and the potentially hazardous air flow profile was monitored by the ACLAIM system.

Jeon, D. and Gharib, M.

"ON THE RELATIONSHIP BETWEEN THE VORTEX FORMATION PROCESS AND CYLINDER WAKE VORTEX PATTERNS"

Journal of Fluid Mechanics, Vol. 519, 2004, pp. 161-181.

The idea of vortex formation time, originally developed for vortex ring formation, is extended to bluff-body flows. Effects related to characteristic vortex formation time are shown for both the cylinder

starting from rest and the cylinder undergoing forced oscillations in a steady flow. By looking at how wake vortices are formed when the cylinder is accelerated from rest, it is found that similarities exist between the formation process for wakes and for vortex rings. This formation process is then observed for forced oscillating cylinders, where the characteristic formation time interacts with the oscillation period. Frequently observed bluff-body phenomena will be recast considering the vortex formation process.

Jeong, J. and Hussain, F.

"ON THE IDENTIFICATION OF A VORTEX"

J. of Fluid Mech., Vol. 285, February 1995, pp. 69-94

Considerable confusion surrounds the longstanding question of what constitutes a vortex, especially in a turbulent flow. This question, frequently misunderstood as academic, has recently acquired particular significance since coherent structures (CS) in turbulent flows are now commonly regarded as vortices. An objective definition of a vortex should permit the use of vortex dynamics concepts to deduce CS, to explain formation and evolutionary dynamics of CS, to explore the role of CS in turbulence phenomena, and to develop viable turbulence models and control strategies for turbulence phenomena. We propose the definition of a vortex in an incompressible flow in terms of the eigenvalues of the symmetric tensor $S/\sup 2/ + \Omega / \sup 2/$; here S and Ω are respectively the symmetric and antisymmetric parts of the velocity gradient tensor $\text{Del } u$. This definition captures the pressure minimum in a plane perpendicular to the vortex axis at high Reynolds numbers, and also accurately defines vortex cores at low Reynolds numbers, unlike a pressure-minimum criterion. We compare our definition with prior schemes/definitions using exact and numerical solutions of the Euler and Navier-Stokes equations for a variety of laminar and turbulent flows. In contrast to definitions based on the positive second invariant of $\text{Del } u$ or the complex eigenvalues of $\text{Del } u$, our definition accurately identifies the vortex core in flows where the vortex geometry is intuitively clear.

Jeong, M.-S., Lee, I., Yoo, S.-J., Yun, C. Y. and Kim, D.-K.

"WAKE EFFECTS ON AEROELASTIC STABILITY OF HINGELESS AND BEARINGLESS ROTORS"

Journal of Aircraft, Vol. 50, No. 6, November-December 2013, pp. 1938-1943.

In the present work, a study of the wake effects on the aeroelastic stability of hinge-less and bearing-less helicopter rotors was investigated in forward flight. A nonlinear beam model based on the large deflection theory was employed to evaluate the aeroelastic responses. To calculate the air loads of the rotor blades, three different aerodynamic approaches were used: a 2-D quasi steady with a Drees linear inflow model, the blade element theory (BET) with a Drees linear inflow model, and the BET with a free-wake method. As a result of the differences in the aerodynamic methods, the results of the periodic tip deflection exhibited discrepancies. In addition, the flap, lag, and torsion damping values obtained from the stability analyses of the hinge-less rotor blades were compared with those from previous studies. The lag damping obtained from the BET with the free-wake method, which differs by

at least 14.6 percent at low forward speeds, had lower values than the other approaches. At a low advance ratio, the damping values were significantly influenced by the wake effect. For this reason, it was clearly seen that the discrepancies of the damping values disappeared as the forward speed increased. Moreover, comparisons of the lag damping values of the bearing-less rotor blade obtained using the present analysis with experiments and other types of analyses exhibited reasonable agreement with some notable differences emanating from the wake effects. Therefore, it is concluded that the wake effects should be considered in order to obtain an accurate estimation of the aeroelastic stability.

Jewell, W. F. and Stapleford, R. L.

"MATHEMATICAL MODELS USED TO SIMULATE AIRCRAFT ENCOUNTERS WITH WAKE VORTICES"

STI TR-1035-4, August 1975, Systems Technology Inc., Mountain View, CA

The mathematical model described herein was used for piloted simulation of aircraft encounters with wake vortices. It was implemented on a large moving base simulator (Flight Simulator for Advanced Aircraft) at National Aeronautics and Space Administration's Ames Research Center. The simulation covered two penetrating aircraft, the Lear-23 and the Boeing 720.

Jian, T. and Ke-Qin, Z.

"NUMERICAL AND EXPERIMENTAL STUDY OF FLOW STRUCTURE OF LOW-ASPECT RATIO WING"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1196-1201

Unsteady aerodynamic characteristics of a low-aspect-ratio elliptic wing with an E-174 airfoil are studied by numerically solving unsteady incompressible Navier-Stokes equations. Two phenomena have been found: The first phenomenon is found at angle of attack larger than 11 deg, where the flow around the wing becomes bilateral asymmetric. This phenomenon is caused by tip vortices' destabilization. Tip vortices' destabilization is due to interaction between a secondary separated vortex and the tip vortices. The second phenomenon is found at angle of attack larger than 33 deg, where a large separated vortex stays above the wing, forming a stationary vortex. The stationary vortex is thought to be related to the vertical component of the tip vortices. Experimental flow visualization has verified the phenomena found in the numerical simulation.

Jianbing, L., Hang, G., Tao, W. and Xuesong, W.

"A SURVEY OF THE SCATTERING CHARACTERISTICS AND DETECTION OF AIRCRAFT WAKE VORTICES"

Journal of Radars, Vol. 6, 2017, pp. 1-20.

Aircraft wake vortex is a pair of strong counter-rotating vortices and has attracted considerable attention in various fields including aviation safety and atmospheric physics. The characteristics and detection of wake vortex act as the basis for both behavior prediction as well as hazard assessment.

This paper provides a short survey of the characteristics and detection researches. Initially, the wake vortex is classified as clear-air wake vortex (i.e., wake turbulence and contrail) and precipitation wake vortex (i.e., under rainy, foggy, or snowy condition). Subsequently, the dynamics and scattering are introduced, and the main verdicts are: the radar (radio detection and ranging) scattering of wake vortex is relatively weak under clear air conditions, but the Lidar (Light detection and ranging) scattering is appreciable owing to the presence of particles such as aerosols. Wake vortices under precipitation conditions and contrails possess relatively good radar reflectivity owing the strong scattering characteristics of precipitation droplets and ice crystals. Furthermore, we have introduced a joint detection scheme of Lidar and radar for wake vortex along with parameter-retrieval algorithms. Finally, we have presented our conclusions and intended future research.

Jiang, L., Cai, J. and Liu, C.

"LES FOR INTERACTION OF WINGTIP VORTEX AND WAKES"

AIAA Paper No. 2007-724, Reno, NV, January 2007

Large eddy simulation with filtered-structured-function sub-grid model and implicit large eddy simulation (ILES without explicit sub-grid model) using high-order accuracy and high-resolution compact scheme have been performed on the tip vortex shedding from a rectangular half-wing with a NACA 0012 airfoil section and a rounded wing tip. The formation of the tip vortex and its initial development in the boundary layer and the near field wake are investigated and analyzed in detail. The physics, why the tip vortex, which is originally turbulent in the boundary layer, is relaminarized and becomes stable and laminar rapidly after shedding in the near field, is revealed by this simulation. The computation also shows the widely used second order sub-grid model is not consistent to six-order compact scheme and would degenerate the six-order LES results to second order. Therefore, high order schemes, grid refinement and six order sub-grid models are critical to LES approaches.

Jiang, L., Cai, J. and Liu, C.

"LES FOR NEAR FIELD WAKES BEHIND JUNCTION OF WING AND PLATE"

Journal of Hydrodynamics, Vol. 18, Issue 3, Supplement 1, July 2006, pp. 270-274

Large eddy simulation with high-order accuracy and high resolution has been performed on the tip vortex shed from a rectangular half-wing with a NACA 0012 airfoil section and a rounded wing tip. The formation of the tip vortex and its initial development in the near field are studied and analyzed in details.

Jiang, L., Cai, J. and Liu, C.

"LARGE EDDY SIMULATION OF WING TIP VORTEX IN THE NEAR FIELD"

Technical Report 2007-13, September 2007, University of Texas, Arlington, TX

Large eddy simulation with filtered-structure-function sub-grid model and implicit large eddy simulation (ILES without explicit sub-grid model) using high-order accuracy and high-resolution compact scheme have been performed on the tip vortex shedding from a rectangular half-wing with a NACA 0012 airfoil section and a rounded wing tip. The formation of the tip vortex and its initial development in the boundary layer and the near field wake are investigated and analyzed in detail. The physics, why the tip vortex, which is originally turbulent in the boundary layer, is relaminarized and becomes stable and laminar rapidly after shedding in the near field, is revealed by this simulation. The computation also shows the widely used second order sub-grid model is not consistent to six-order compact scheme and would degenerate the six-order LES results to second order. Therefore, high order schemes, grid refinement and six order sub-grid models are critical to LES approaches.

Jiang, M., Machiraju, R. and Thompson, D. S.

"DETECTION AND VISUALIZATION OF VORTICES"

Visualization Handbook, edited by C. Johnson and C. Hansen, Academic Press, 2004, pp. 287-301.

Throughout the past decade, there has been a steady stream of publications about vortex detection. The paper presents an overview of nine detection algorithms that are representative of the state-of-the-art. Each detection algorithm is classified based on how it defines a vortex, whether it is Galilean invariant, and the local or global nature of its identification process. Although many of the algorithms share similarities, each has its own advantages and disadvantages. A recently developed verification algorithm, that can be used in conjunction with any detection method, was also overviewed, as well as various techniques for visualizing detected vortices. Although much progress has been made towards detecting vortices in steady flow fields, there is still a paucity of methods that can do the same in unsteady (time-varying) flow fields. None of the detection methods described in this paper can adequately address all of the issues unique to unsteady vortical flows. A major challenge will be to develop efficient and robust vortex detection and tracking algorithms for unsteady flow fields.

Jimenez, A., Migoya, E., Esteban, M., Gimenez, D., Garcia, J. and Crespo, A.

"INFLUENCE OF TOPOGRAPHY AND WAKES ON WIND TURBULENCE: MEASUREMENTS AND INTERPRETATION OF RESULTS"

Wind Energy, Vol. 14, Issue 7, October 2011, pp. 895-908.

To perform detailed calculations of dynamic loads on wind turbines due to turbulence, a precise wind simulator is needed. International standards give guidelines to generate a synthetic wind for a flat terrain in the absence of wakes. Measurements in complex terrain and under wake effects have been analyzed with the purpose of establishing some modifications to those guidelines that improve the simulated wind turbine characteristics. A modification of the spectrum shape is proposed for locations affected by wind turbine wakes. Modifications are also proposed for the ratios of standard deviations and the turbulence lengths, which give a tendency to turbulence isotropy, as the complexity of the

terrain and wake effects become more relevant. The parameter called normalized turbulence intensity is introduced to quantify the 'complexity' of a location.

Jimenez, J.

"STABILITY OF A PAIR OF CO-ROTATING VORTICES"

Phys. Fluids, Vol. 18, No. 11, November 1975, pp. 1580-1581

The linear stability of a pair of co-rotating vortex filaments is studied with a view toward clarifying the behavior of these pairs in the shear layer. The configuration is found to be stable within the long wave approximation.

Jimenez, J. M. and Smits, A. J.

"TIP AND JUNCTION VORTICES GENERATED BY THE SAIL OF A YAWED SUBMARINE MODEL AT LOW REYNOLDS NUMBERS"

Journal of Fluids Engineering, Vol. 133, March 2011, pp. 034501-1 to 034501-4.

Results are presented on the behavior of the tip and junction vortices generated by the sail of a SUBOFF submarine model at yaw angles from 6 deg. to 17 deg. for a Reynolds number of 94,000 based on model length. The measurements were conducted in a water channel on a spanwise plane 1.3 chord lengths downstream from the trailing edge of the sail. In the vicinity of the sail hull junction, the pressure of streamwise vortices in the form of horseshoe or necklace vortices locally dominates the flow. As the yaw angle is increased from 6 deg. to 9 deg., the circulation of the sail tip vortex increases, and is in good accordance with predictions from finite wing theory. However, as the yaw angle is further increased, the sail boundary layer separates with an overall drop in circulation. In contrast, the circulation value for the junction vortex increases with yaw angle, and only drops slightly at the highest yaw angle.

Jimenez-Garcia, A., Barakos, G. N., Treve, V., Rooseleer, F., Cappellazzo, V. and Graham, R.

"HELICOPTER WAKE ENCOUNTERS IN THE CONTEXT OF RECAT-EU"

43rd European Rotorcraft Forum, Paper 512, September 2017, Milan, Italy.

This work presents a first attempt to apply the RECAT-EU (European Wake Turbulence Categorization and Separation Minima) methodology of fixed-wing aircraft separation to helicopters. The approach is based on a classification of helicopters in categories using their rotor diameter and weight combined with wake comparisons between different classes of fixed-wing aircraft and helicopters. Where necessary the upset caused by a wake encounter to a simple helicopter model is used to establish safe separation distances. The work is based on a very limited amount of data for wake strengths but shows that the principles of the RECAT-EU methodology are directly applicable to helicopters at least for landing and take-off. This research calls for further measurements of helicopter wakes with modern

methods so that the suggested separation distances can be further ascertained and ultimately refined allowing for better and safer integration of fixed and rotary-wing traffic at airports.

Jin, J., Oh, S., Yee, K. and Kwon, K.

"TRAILING VORTEX STRENGTH ATTENUATION VIA CHIPPED WINGTIP SHAPES"

AIAA Paper 2013-2656, June 2013, San Diego, CA.

The shedding of strong vortices generated at the wingtip during take off and landing can cause substantial safety issue to the following aircraft. To avoid the vortex wake hazard from the leading aircraft, a chipped wingtip shape is proposed as a new concept and its conceptual validity is examined through systematic wind tunnel studies. The flow structure of the vortex wakes behind chipped wingtip shapes are measured by using particle image velocimetry (PIV) at $Re = 1,060,000$. Aerodynamic forces of chipped wingtip shapes are also measured to supplement the PIV results. It is found that the trailed vortices of chipped wingtip shapes are substantially attenuated compared with those of the baseline wingtip shape. Counter-rotating vortices generated by chipped wingtip shape significantly weakens the main wingtip vortex strength in the far field. A series of parametric study has been performed to evaluate the chip shape parameters such a chip aspect ratio, spacing from wingtip edge and area percentage. From the results it is concluded that despite a slight increase of the drag, chipped wingtip shape can successfully alleviate the peak tangential velocity and vorticity strength of the trailed vortices.

Jing, F., Kanso, E. and Newton, P. K.

"INSIGHTS INTO SYMMETRIC AND ASYMMETRIC VORTEX MERGERS USING THE CORE GROWTH MODEL"

Physics of Fluids, Vol. 24, 2012, pp. 073101-1 - 073101-17.

We revisit the two-vortex merger problem (symmetric and asymmetric) for the Navier-Stokes equations using the core growth model for vorticity evolution coupled with the passive particle field and an appropriately chosen time-dependent rotating reference frame. Using the combined tools of analyzing the topology of the streamline patterns along with the careful tracking of passive fields, we highlight the key features of the stages of evolution of vortex merger, pinpointing deficiencies in the low-dimensional model with respect to similar experimental/numerical studies. The model, however, reveals a far richer and delicate sequence of topological bifurcations than has previously been discussed in the literature for this problem, and, at the same time, points the way towards a method of improving the model.

Johannes, R. P.

"AIRCRAFT WAKE TURBULENCE CONTROLLABILITY EXPERIMENT"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 547-559.

The object of the experiment was to evaluate the effectiveness of a properly mechanized automatic control system in minimizing aircraft upset and improving the controllability which can result from wake turbulence encounter. The in-flight experiment consisted of two flights of approximately three hours duration each, wherein the B-52 test aircraft was flown in formation with a C-141 and explored the wake turbulence generated.

Johansson, B. C. A.

"COMPRESSIBLE FLOW ABOUT HELICOPTER ROTORS"

Vertica, Vol. 2, No. 1, pp. 1-9

Two theoretical methods for helicopter rotors or propellers in subsonic flow are presented, namely a lifting-line theory for a helicopter rotor in vertical climb, hovering or in slow descent, or a propeller in steady forward flight or operating statically, and a disk approximation for a helicopter rotor in forward flight or a propeller in yaw. In both methods the compressibility of the air is considered. In the second case, the rotor is approximated by a disk of continuous thrust and in-plane force distributions, which are assumed to be known. Its wake is represented by a semi-infinite cylinder of distributed vorticity. Formulas for the induced velocity field are derived.

Johansson, L. C., Wolf, M. and Hedenstrom, A.

"A QUANTITATIVE COMPARISON OF BIRD AND BAT WAKES"

Journal of the Royal Society Interface, Vol. 7, 2009, pp. 61-66.

Qualitative comparison of bird and bat wakes has demonstrated significant differences in the structure of the far wake. Birds have been found to have a unified vortex wake of the two wings, while bats have a more complex wake with gradients in the circulation along the wingspan, and with each wing generating its own vortex structure. Here, we compare quantitative measures of the circulation in the far wake of three bird and one bat species. We find that bats have a significantly stronger normalized circulation of the start vortex than birds. We also find differences in how the circulation develops during the wingbeat as demonstrated by the ratio of the circulation of the dominant start vortex and the total circulation of the same sense. Birds show a more prominent change with changing flight speed and a relatively weaker start vortex at minimum power speed than bats. We also find that bats have a higher normalized wake loading based on the start vortex, indicating higher relative induced drag and therefore less efficient lift generation than birds. Our results thus indicate fundamental differences in the aerodynamics of bird and bat flight that will further our understanding of the evolution of vertebrate flight.

Johansson, P. B. V.

"THE AXISYMMETRIC TURBULENT WAKE"

PhD Thesis, 2002, Chalmers University of Technology, Goteborg, Sweden.

This thesis presents a theoretical and experimental study of the turbulent axisymmetric wake. In the theoretical part, an equilibrium similarity solution of the far wake was derived that was found to admit to two different solutions for this flow. The high Reynolds number solution predicts that the flow grows as the cube root of the distance downstream, whereas the low Reynolds number solution grows as the square root of the downstream distance. None of these solutions had unambiguously been confirmed in earlier work. The analysis also provided necessary criteria for when to expect either solution. In the experimental part, data was obtained by hot-wire anemometry using arrays of 13 and 15 probes. For the first time, experimental data was proven to behave like the high Reynolds number equilibrium similarity solution predicted. These multi-point probe rakes were also used to measure cross-spectra in cross-sections of the flow from 10 to 150 disk diameters downstream.

Johari, H. and Durgin, W. W.

"DIRECT MEASUREMENT OF CIRCULATION USING ULTRASOUND"

Experiments in Fluids, Vol. 25, 1998, pp. 445-454

Ultrasound time-of-flight methods employing counter-propagating ultrasonic pulses are utilized for the direct measurement of circulation in vortical flows. Two schemes are described here which involve either a single straight path or a closed path. Both techniques are shown to result in time differences, between the counter-propagating pulses around the path, linearly proportional to the circulation enclosed by the ultrasound path. The ultrasound methods of circulation measurement do not require calibration constants and can be non-invasive. The reliability of the closed path ultrasound method was assessed by comparing the measured circulation values with those calculated from the lift measurements of a NACA 0012 airfoil. Two examples are also presented where the closed path ultrasound method has been applied to the flow over a delta wing and a free-surface vortex in a cylindrical tank.

Johari, H. and Durgin, W. W.

"ULTRASONIC MONITORING METHOD AND SYSTEM FOR WAKE TURBULENCE USEFUL AT RUNWAYS"

US Patent 6,062,076, May 2000.

Two techniques for detecting vortices and their associated circulation are disclosed. The first is termed a closed path configuration, and the second is termed the dual path configuration. These techniques are useable for the detection of wake turbulence especially in the vicinity of airport runways, which results from wing tip vortices generated by aircraft during take-off and landing. The systems are similar in that they use ultrasonic measurement techniques to determine the circulation about defined areas. The circulation is reflective of the vorticity associated with trailing vortices, which are manifest within the area.

Johari, H. and Moreira, J.

"DIRECT MEASUREMENT OF DELTA-WING VORTEX CIRCULATION"

AIAA Journal, Vol. 36, No. 12, December 1998, pp. 2195-2203.

The circulation around a closed path encompassing the primary vortex of stationary delta wings has been investigated using a novel ultrasound technique. Ultrasonic pulses propagating in clockwise and counterclockwise directions enclosed a fixed path that was positioned perpendicular to the delta-wing root chord line. Circulation in the plane of the closed path then was determined from the transit-time difference between the clockwise and counterclockwise pulses. Half-delta wings with sweep angles of 60 and 70 deg were tested over a range of angles of attack up to 38 deg and 52 deg, respectively, and at chordwise distances of 35, 50, 65, and 80 percent from the wing apexes. Circulation increased monotonically with angle of attack for both sweep angles until it reached a maximum value, beyond which the total circulation decreased or remained nearly constant. The angle of attack associated with the maximum circulation is correlated with conditions resulting in feeding sheet interaction on the symmetry plane. At any angle of attack, circulation increased approximately linearly with increasing chordwise location as long as the feeding-sheet interaction was not present. Normalizing circulation by freestream velocity and local semispan collapsed the data at angles of attack prior to the interaction. The rate of circulation increase along the wing increased with angle of attack for both sweep angles. Vortex breakdown does not appear to have any direct influence on the total circulation of delta-wing vortices.

Johnson III, W., Trickey, C., Forsythe, J., Albertson, J. and Leigh, E.

"EXPERIMENTAL AND COMPUTATIONAL INVESTIGATION OF THE FLOW BEHIND A C-130 WITH TAILGATE DOWN"

AIAA Paper 2002-0713, January 2002, Reno, NV.

This paper presents a comparison of computational fluid dynamics and an experimental analysis of the unsteady flow behind a C-130 with tailgate down. One of the primary missions of the C-130 Hercules is deployment of airborne paratroopers using a static line system to deploy the parachutes. However, if the static line fails to deploy the paratroopers may get caught and injured in the separation/recirculation region aft of the cargo bay ramp. A detailed experimental and computational understanding of the nature of the flow has been initiated at the US Air Force Academy to identify solutions to this problem. An unstructured grid modeling the full aircraft with 6,200,000 cells was created, and an unsteady Navier Stokes solution was performed, matching the experimental Reynolds number. The experimental analysis involves laser light sheet and dye flow visualization coupled with particle image velocimetry. The potential solutions of extending a large plate/extended ramp out of the cargo bay ramp as well as using bleed doors along the fuselage are identified and examined.

Johnson Jr, E. J.

"TOLERABLE ERRORS IN MEAN EDR FOR WAKE TURBULENCE APPLICATIONS"

AIAA Paper 2017-4241, June 2017, Denver, CO.

The prediction of aircraft wake turbulence lifetimes has been identified as potentially the primary user of mean Eddy Dissipation Rate (EDR) data derived from aircraft-based observations. This paper develops estimates for the error in EDR values that can be tolerated without affecting the prediction of wake vortex lifetimes by more than 5 percent across the range of EDR values operationally significant for potential wake turbulence applications. These estimates were used by the FAA to develop performance standards for algorithms computing EDR from aircraft derived data. The FAA performance standards are being leveraged by RTCA Special Committee 206 to develop performance guidelines and requirements for algorithms computing EDR to ensure operationally comparable results under all conditions normally encountered in routine aeronautical operation.

Johnson, A.

"TRENDS IN WAKE VORTEX INCIDENTS"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 9-1 - 9-12

An analysis of 140 incidents involving wake vortex turbulence over the past 7 years was undertaken to detect trends in these reports. After processing the files, patterns appeared. It was found that most wake vortex incidents occur when a plane of the 'large' weight class is preceded by a plane of the 'heavy' class. Moreover, a large fraction of the incidents with the heavy/large and the large/large combination had the required spacing required by federal regulations, and most of the incidents happened in the landing/approach phase of the plane's flight, below 1000'.

Johnson, D. E.

"DEVELOPMENT OF A TERMINAL SENSOR FOR HAZARDOUS WEATHER AND WAKE TURBULENCE DETECTION"

Annual Assembly Meeting and Technical Symposium Proceedings, Radio Technical Commission for Aeronautics, 1984, pp. 149-158.

It is pointed out that real time weather information for Federal Aviation Administration (FAA) air traffic control (ATC) purposes comes currently from ATC surveillance radars. However, existing surveillance radars have three severe limitations for weather detection use. One limitation is related to an optimization of the radars for aircraft detection, because such an optimization degrades the weather detection capability. The fan beam antenna of the surveillance radars causes inaccuracies in weather indications, while the third limitation is the restriction of the surveillance radars to the provision of reflectivity information. This situation has led the FAA to conduct research and development activities concerning the use of Doppler radars. Attention is given to the FAA weather radar requirements, activities in support of the Next Generation Weather Radar (NEXRAD), wind shear and wake turbulence detection, and aspects of data collection.

Johnson, H.

"NONLINEAR DYNAMICS OF WAKE VORTICES"

PhD Thesis, December 2016, University of Paris-Saclay, Ecole Polytechnique, Paris, France.

Aircraft wakes have been the subject of extensive research for several decades as it poses economic, safety and environmental issues. The wake is composed of powerful counter-rotating vortices that persist long after the aircraft has passed. In this thesis, the nonlinear dynamics of aircraft wake vortices is investigated through Direct Numerical Simulation. The aim is to explore the nonlinear effects on wake vortex behavior and evaluate the potential for the anticipated destruction of the vortices through optimal perturbation. First the disruptive potential of the linear optimal perturbation of the flow is evaluated by applying it with increasing initial amplitude and observing the nonlinear response of the flow. With sufficient yet reasonable initial amplitude, the linear optimal perturbation halves the life-span of the vortex pair by accelerating the loss of coherence of the vortices after the linking phase. Next the nonlinear gradient-based optimization tool that was developed during the thesis is validated by reproducing existing results concerning a simple vortical flow: an isolated two-dimensional vortex. In doing so new nonlinear optimization results are obtained and analyzed. It is shown that the 2D nonlinear optimal perturbation of an isolated vortex can induce considerably greater transient growth than the linear optimal. In some cases, the nonlinear optimal causes a transition to a quasi-steady asymmetric state, bypassing the natural axisymmetrization process. The effect of the vortex vorticity profile on the optimal perturbations is also studied. Vortices with sharper profiles experience far greater linear perturbation growth, however the nonlinear growth is significantly inferior. Finally, the nonlinear optimal perturbation analysis of the isolated vortex is extended to three dimensions. Although the 3D nonlinear optimal perturbations produce less growth than their linear counterparts, they can lead to quasi-permanent high energy states.

Johnson, P. B., Jonsson, C., Achilleos, S. and Eames, I.

"ON THE SPREAD AND DECAY OF WIND TURBINE WAKES IN AMBIENT TURBULENCE"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012055-1 - 012055-8.

The decay of the downstream wake turbine plays an important role in the performance of a wind farm. The spread and decay of a wake depend both on wake meandering (advection of the wake as a whole) and wake diffusion (widening of the wake within its meandering frame of reference). Both of these effects depend strongly on the intensity of the ambient turbulence relative to the velocity deficit in the wake, and on the integral length scale of the turbulence relative to the wake width. Recent theory, which we review here, shows how intense large-scale turbulence can lead to a rapid $1/(x^2)$ decay in the time-averaged centerline velocity deficit, as compared to a $1/x$ decay for smaller scale turbulence, where x is distance downstream. We emphasize in this paper that common wind farm models do not predict this rapid decay. We present new experimental measurements of the velocity deficit downstream of a porous disc in relatively large-scale ambient turbulence which

corroborate predictions of a $1/(x \text{ squared})$ decay, and we show theoretically that the commonly used k-epsilon model does not capture this effect. We further show that a commercial CFD package, configured to match our experiments and employing the k-epsilon model, fails to predict such rapid decay. We conclude that steady simulations of wind turbine wake dynamics are insufficient for informing wind farm layout optimization.

Johnson, S. C., Lohr, G. W., McKissick, B. T., Abbott, T. S., Guerreiro, N. M. and Volk, P.

"SIMPLIFIED AIRCRAFT-BASED PAIRED APPROACH: CONCEPT DEFINITION AND INITIAL ANALYSIS"

NASA/TP-2013-217994, January 2013, NASA Langley Research Center, Hampton, VA.

Simplified Aircraft-based Parallel Approach (SAPA) is an advanced concept proposed by the Federal Aviation Administration (FAA) to support dependent parallel approach operations to runways with lateral spacing closer than 2500 ft. At the request of the FAA, NASA performed an initial assessment of the potential performance and feasibility of the SAPA concept, including developing and assessing an operational implementation of the concept and conducting a Monte Carlo wake simulation study to examine the longitudinal spacing requirements. The SAPA concept was shown to have significant operational advantages in supporting the pairing of aircraft with dissimilar final approach speeds. The wake simulation study showed that support for dissimilar final approach speeds could be significantly enhanced using a two-phase altitude-based longitudinal positioning requirement, with larger longitudinal positioning allowed for higher altitudes out of ground effect and tighter longitudinal positioning defined for altitudes near and in ground effect. While this assessment is preliminary and there are several operational issues still to be examined, it has shown the basic SAPA concept to be technically and operationally feasible.

Johnson, W.

"MODEL FOR VORTEX RING STATE INFLUENCE ON ROTORCRAFT FLIGHT DYNAMICS"

4th Decennial Specialist's Conference on Aeromechanics, American Helicopter Society, January 2004, San Francisco, CA.

The influence of vortex ring state (VRS) on rotorcraft flight dynamics is investigated, specifically the vertical velocity drop of helicopters and the roll-off of tiltrotors encountering VRS. The available wind tunnel and flight test data for rotors in vortex ring state are reviewed. Test data for axial flow, nonaxial flow, two rotors, unsteadiness, and vortex ring state boundaries are described and discussed. Based on the available measured data, a VRS model is developed. The VRS model is a parametric extension of momentum theory for calculation of the mean inflow of a rotor, hence suitable for simple calculations and real-time simulations. This inflow model is primarily defined in terms of the stability boundary of the aircraft motion. Calculations of helicopter response during VRS encounter were performed, and good correlation is shown with the vertical velocity drop measured in flight tests. Calculations of tiltrotor response during VRS encounter were performed, showing the roll-off behavior characteristic of

tiltrotors. Hence it is possible, using a model of the mean inflow of an isolated rotor, to explain the basic behavior of both helicopters and tiltrotors in vortex ring state.

Johnson, W.

"INFLUENCE OF WAKE MODELS ON CALCULATED TILTROTOR AERODYNAMICS"

American Helicopter Society Aerodynamics, Acoustics, and Test and Evaluation Technical Specialists Meeting, January 2002, San Francisco, CA.

Comparisons of measured and calculated aerodynamic behavior of a tiltrotor model are presented. The test of the Tilt Rotor Aeroacoustic Model (TRAM) with a single, 1/4-scale V-22 rotor in the German-Dutch Wind Tunnel (DNW) provides an extensive set of aeroacoustic, performance, and structural loads data. The calculations were performed using the rotorcraft comprehensive analysis CAMRAD II. Presented are comparisons of measured and calculated performance and air loads for helicopter mode operation, as well as calculated induced and profile power and wake geometry. The focus of this paper is on the further development of wake models for tiltrotors in helicopter mode operation. Three tiltrotor wake models are considered, characterized as the rolled-up, multiple-trailer, and multiple-trailer with consolidation models. By using a free wake geometry calculation method that combines the multiple-trailer wake model with a simulation of the tip vortex formation process (consolidation), good correlation of the calculations with TRAM measurements is obtained for both performance and for air loads.

Johnson, W. A.

"MATHEMATICAL MODEL FOR HUMAN PILOT BEHAVIOR DURING A WAKE VORTEX ENCOUNTER UPSET"

TR-1025-4/2, May 1975, Systems Tech. Inc., Hawthorne, CA.

This report documents the results of a pilot modeling effort to determine the roll control behavior of a human pilot during a wake vortex encounter upset. Data for the pilot modeling analysis was obtained from a six-degree-of-freedom moving-base, piloted simulation of vortex encounters at NASA Ames Research Center.

Johnson, W. A. and Myers, T. T.

"A MODEL FOR HUMAN PILOT BEHAVIOR DURING WAKE VORTEX ENCOUNTER UPSETS"

FAA-RD-76-8, April 1976, Systems Technology Inc., Hawthorne, CA.

A model for pilot behavior is needed to more completely analyze the consequences (including hazard assessment) of wake vortex encounter upsets during final approach. Such a model has been developed to describe a pilot's roll control behavior during a vortex upsets. This model resulted from abstracting the salient characteristics of the many vortex encounters recorded during two moving-base piloted simulations at NASA Ames Research Center. The model allows for several discrete modes of behavior

and includes an associated set of switching logics. The model is the result of a lengthy sequence of analytical steps; however, a retracing of these steps is not included here. Rather, only a description of the resulting model and several example applications are presented.

Johnson, W. A. and Rediess, H. A.

"STUDY OF CONTROL SYSTEM EFFECTIVENESS IN ALLEVIATING VORTEX WAKE UPSETS"

AIAA Paper No. 1973-0833, Key Biscayne, FL, 1973.

The problem of an airplane being upset by encountering the vortex wake of a large transport on takeoff or landing is currently receiving considerable attention. This paper describes the technique and results of a study to assess the effectiveness of automatic control systems in alleviating vortex wake upsets. A six-degree-of-freedom nonlinear digital simulation was used for this purpose. The analysis included establishing the disturbance input due to penetrating a vortex wake from an arbitrary position and angle. Simulations were computed for both a general aviation airplane and a commercial jet transport. Dynamic responses were obtained for the penetrating aircraft with no augmentation, and with various command augmentation systems. The results of this preliminary study indicate that it is feasible to use an automatic control system to alleviate vortex encounter upsets.

Johnson, W. A. and Teper, G. L.

"ANALYSIS OF VORTEX WAKE ENCOUNTER UPSETS"

NASA CR-127491, August 1974, Systems Tech. Inc., Hawthorne, CA

The problem of an airplane being upset by encountering the vortex wake of a large transport on takeoff or landing is currently receiving considerable attention. This report describes the technique and result of a study to assess the effectiveness of automatic control systems in alleviating vortex wake upsets. A six-degree-of-freedom nonlinear digital simulation was used for this purpose. The analysis included establishing the disturbance input due to penetrating a vortex wake from an arbitrary position and angle. Simulations were computed for both a general aviation airplane and a commercial jet transport. Dynamic responses were obtained for the penetrating aircraft with no augmentation, and with various command augmentation systems, as well as with human pilot control. The results of this preliminary study indicate that attitude command augmentation systems can provide significant alleviation of vortex wake upsets; and can do it better than a human pilot.

Johnson, W. A., Teper, G. L. and Rediess, H. A.

"STUDY OF CONTROL SYSTEM EFFECTIVENESS IN ALLEVIATING VORTEX WAKE UPSETS"

Journal of Aircraft, Vol. 11, No. 3, March 1974, pp. 148-154

The problem of an airplane being upset by encountering the vortex wake of a large transport on takeoff or landing is currently receiving considerable attention. This paper describes the technique and

results of a study to assess the effectiveness of automatic control systems in alleviating vortex wake upsets. A six-degree-of-freedom nonlinear digital simulation was used for this purpose. The analysis included establishing the disturbance input due to penetrating a vortex wake from an arbitrary position and angle. Simulations were computed for both a general aviation airplane and a commercial jet transport. Dynamic responses were obtained for the penetrating aircraft with no augmentation, and with various command augmentation systems. The results of this preliminary study indicate that it is feasible to use an automatic control system to alleviate vortex encounter upsets.

Johnson, W., Yamauchi, G. K., Derby, M. R. and Wadcock, A. J.

"WIND TUNNEL MEASUREMENTS AND CALCULATIONS OF AERODYNAMIC INTERACTIONS BETWEEN TILTROTOR AIRCRAFT"

AIAA Paper 2003-0047, January 2003, Reno, Nevada.

Wind tunnel measurements and calculations of the aerodynamic interactions between two tiltrotor aircraft in helicopter mode are presented. The measured results include the roll moment and thrust change on the downwind aircraft, as a function of the upwind aircraft position (longitudinal, lateral, and vertical). Magnitudes and locations of the largest interactions are identified. The calculated interactions generally match the measurements, with discrepancies attributed to the unsteadiness of the wake and aerodynamic forces on the airframe. To interpret the interactions in terms of control and power changes on the aircraft, additional calculations are presented for trimmed aircraft with gimbaled rotors.

Johnstone, E. H.

"AIRCRAFT WING VORTEX DEFLECTOR"

US Patent 3,974,986, August 1976.

An aircraft wing vortex deflector constituting means for intercepting at least part of the spiral flow of air around the tips of the wings during flight and directing the intercepted air rearwardly in a manner and direction tending to dissipate vortices in the wake of the aircraft.

Joly, L. and Reinaud, J. N.

"THE MERGER OF TWO-DIMENSIONAL RADIALLY STRATIFIED HIGH-FROUDE-NUMBER VORTICES"

J. Fluid Mech., Vol. 582, 2007, pp. 133-151

We investigate the influence of density inhomogeneities on the merger of two co-rotating two-dimensional vortices at infinite Froude number. In this situation, buoyancy effects are negligible, yet density variations still affect the flow by pure inertial effects through the baroclinic torque. We first re-address the effects of a finite Reynolds number on the interaction between two identical Gaussian vortices. Then, by means of direct numerical simulations, we show that vortices transporting light fluid

in a heavier counterpart merge from further distances than vortices in a uniform density medium. On the other hand, heavy vortices only merge from small separation distances. We measure the critical distance of the vortex radii to their initial separation distance. It departs from the homogeneous threshold of 0.22 in response to increasing density contrasts between the vortices and their surroundings. An analysis of the contribution of the baroclinic vorticity to the dynamics of the flow is detailed and explains the observed behavior. This analysis is completed by a simple model based on point vortices that mimics the flow. It is concluded that vortices carrying light fluid are more likely to generate large-scale structures than heavy ones in an inhomogeneous fluid.

Jones, D. N.

"INTRODUCTION TO JET-ENGINE EXHAUST AND TRAILING VORTEX WAKES"

TR-226, April 1970, Air Weather Service (MAC), USAF, Scott Air Force Base, IL.

This report is a result of a survey of the immediately available literature on aircraft wakes and is a general representation of techniques and problems involved. Approximate relations are used for their simplicity and to define areas dangerous to flight.

Jones, J. P.

"THE CALCULATION OF THE PATHS OF VORTICES FROM A SYSTEM OF VORTEX GENERATORS AND A COMPARISON WITH EXPERIMENT"

ARC Report CP-361, March 1955, University of Southampton, Southampton, England.

A method is described for the calculation of the paths of the trailing vortices from a system of counter-rotating vortex generators, and a comparison is made with some experimental results obtained in a water tunnel. The method can be adapted to other configurations of generators arranged to produce rows of vortices close to a plane surface.

Jones, J. P. and Noak, M.

"SOME PROBLEMS IN THE NUMERICAL SOLUTION OF VORTEX MOTION EQUATIONS"

Proceedings of 3rd CAL/AVLABS Symposium, Aerodynamics of Rotor, Wing and V/STOL Aircraft, Vol. III, June 1969.

The results of some flow visualization experiments on the trailing vortices from a model helicopter rotor are presented. It was found that the wake contraction was a cyclic phenomenon dependent on the number of blades. Its precise cause could not be ascertained but was probably due to interference between the blade bound vortices and the trailing vortices in the rotor wake. An investigation was conducted into some of the problems encountered when attempting to solve numerically the equations governing vortex motion.

Jones, M. and Nakamura, Y.

"DYNAMICS OF THE VORTEX CORE DURING PITCHING OF A HIGH-SWEEP DELTA WING"

AIAA Paper No. 2007-1284, Reno, NV, January 2007

In the present work, the pitch-up of a 70-degree sweep delta wing is modelled computationally. The dynamics of the vortex core generated near the wing leading edge, during transitions to vortex breakdown, is observed. The intention is to test theories for breakdown derived from more confined geometries to the delta wing vortex breakdown. Accordingly, the dynamics of the vortex is tracked in terms of the appearance of negative azimuthal vorticity, and transitions in criticality of the vortex core. It is confirmed that the onset of breakdown is preceded in time and space by the generation of negative azimuthal vorticity, consistent with analyses for more confined geometries. Consideration of the criticality criterion, in the form of the helix angle, shows that the chordwise location of breakdown is consistent with the transition of the vortex from a supercritical to subcritical flow.

Jones, M. I. and Bender, E. E.

"CFD-BASED COMPUTER SIMULATION OF OPTICAL TURBULENCE THROUGH AIRCRAFT FLOWFIELDS AND WAKES"

AIAA Paper No. 2001-2798, Anaheim, CA, June 2001

Recent results for Lockheed Martin Aeronautics CFD-based aero-optical analysis of unsteady aerodynamic flow fields are presented. An unsteady CFD analysis of a fuselage/turret configuration is described. The unsteady density fields obtained from the CFD analysis are used to perform aero-optical analysis of laser beams propagating from the turret. Analysis includes time-varying wavefront error (WFE) maps, far-field laser burn patterns, Zernike fitting coefficient values and Zernike spectra for aperture X-tilt, Y-tilt, defocus and astigmatism, and WFE RMS values and RMS spectra.

Jones, R. H.

"HOW THE COURTS LOOK AT WAKE TURBULENCE"

FAA Symposium on Turbulence, Federal Aviation Administration, 1971, p. 23

Wake turbulence aircraft accidents over the years have resulted in law suits against the Government for the alleged negligence of the control tower operator. Recent cases have broadened and extended the liability of the U.S. Government for the negligence of its air traffic controllers in wake turbulence accident cases.

Jones, R. T. and Lasinski, T. A.

"EFFECT OF WINGLETS ON THE INDUCED DRAG OF IDEAL WING SHAPES"

NASA TM-81230, September 1980, NASA Ames Research Center, Moffett Field, CA.

A conventional wing having a given lift and a limited span achieves minimum induced drag when the spanwise distribution of lift is elliptical. However, if the limitation on span is removed and replaced by a structural constraint on the integrated bending moments, Prandtl found that a 10-percent reduction of induced drag can be achieved by a 10-percent increase of wing span accompanied by a more highly tapered loading. In the present report, we have extended such calculations to wings having vertical tip extensions or winglets. It is found that essentially the same result can be obtained by a 15-percent vertical extension. Thus, it appears that with ideal wing shapes similar reductions of induced drag can be achieved by either horizontal or vertical tip extensions.

Jones, S. R.

"POTENTIAL 1090 EXTENDED SQUITTER SUPPORT OF WAKE VORTEX/METEOROLOGY APPLICATIONS"

Report MTR130464, October 2013, Mitre Corporation, McLean, VA.

The Automatic Dependent Surveillance-Broadcast (ADS-B) 1090-Megahertz Extended Squitter message broadcast requirements supporting Wake Vortex and Meteorology data updates are derived from the 'Aircraft Derived Meteorological Data via Data Link for Wake Vortex, Air Traffic Management and Weather Applications -- Operational Services and Environmental Definition (OSED)' (DO-338). Evaluation of the OSED proposed alternatives is based on these requirements as well as an examination of the potential impact of these alternatives on ADS-B users. Criteria for this impact assessment are the 'ADS-B Traffic Surveillance Systems and Applications ADS-B Minimum Aviation System Performance Standards (MASPS)' (DO-338) requirements for state vector updates. Expected performance estimates in specified interference environments use The MITRE Corporation 1090 MHz C0-channel Interference Model. Model validation and expected performance in several interference scenarios proposed by the FAA's 1090 MHz Spectrum Mitigation Alternatives Working Group are described.

Jones, W. P. and Chevalier, H. L.

"AIRCRAFT TRAILING VORTEX INSTABILITIES"

International Council of the Aeronautical Sciences Paper 74-34, Haifa, Israel, 1974. (Also, TEES 600-74-01)

A summary is given of the results of flight test studies of trailing vortices carried out at Texas A&M University. The instability of a pair of trailing vortices due to mutual interaction is fully discussed and theoretical predictions of the wavelength of the vortex oscillations that develop in the far wake of an airplane are compared with values determined from photographic records of the wake behavior of a DeHavilland Beaver DHC-2 aircraft. The different types of instability that can develop with single vortices are also considered, including vortex bursting phenomenon that occurs with vortices that

separate from the leading edges of highly swept wings at incidence. A technique for inducing earlier breakdown and dissipation of the vortices than would occur normally is described.

Jones, W. P. and Rao, B. M.

"AIRLOADS AND MOMENTS ON AN AIRPLANE FLYING OVER A PAIR OF INCLINED TRAILING VORTICES"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 523-545

When an aircraft flies across the wake of a preceding one, it is subjected to changing air loads and moments induced by the trailing vortices of the first aircraft. The purpose of this paper is to investigate the magnitude and characteristics of the time dependent aerodynamic forces so produced. The problem is reduced to finding the appropriate vorticity distribution at each stage of the aircraft's flight over the trailing vortices. This can be done approximately by using a modified lifting line theory or, more accurately, by lifting surface theory.

Jordan, A. R.

"PRESSURE AND VORTICITY TRANSIENTS FROM SUMMER STORMS AND AIRCRAFT"

J. Appl. Meteorology, Vol. 19, October 1980, pp. 1223-1233.

Pressure, wind, and vorticity have been studied on the microscale and mesoscale for a variety of features including plumes, vortices, dust devils, and gust front from thunderstorms along with aircraft-generated vortices. Results confirm the fact that negative-pressure pulses result from updrafts associated with convective elements, both rotational and non-rotational. It is shown that wake vortices from aircraft at take-off and landing have similar features with naturally occurring vortices even though the axes of the wake vortices are initially almost horizontal. It is also shown that a high-sensitivity pressure sensor in combination with suitable wind sensors can be used to determine the diameter and orbital velocity of the vortex flow near the ground where a potential hazard to flight may exist.

Jordan, Jr., F. L.

"FLOW VISUALIZATION OF THE WAKE OF A TRANSPORT AIRCRAFT MODEL WITH LATERAL-CONTROL OSCILLATIONS"

NASA TM-84623, June 1983, NASA Langley Research Center, Hampton, VA

An exploratory flow visualization study conducted in the Langley Vortex Research Facility to investigate the effectiveness of lateral control surface oscillations as a potential method for wake vortex attenuation on a 0.03 scale model of a wide body jet transport aircraft is described. Effects of both asymmetric surface oscillation (control surfaces move as with normal lateral control inputs) and symmetric surface oscillation (control surfaces move in phase) are presented. The asymmetric case simulated a flight maneuver which was previously investigated on the transport aircraft during NASA/FAA flight tests and which resulted in substantial wake vortex attenuation. Effects on the model

wake vortex systems were observed by propelling the model through a two-dimensional smoke screen perpendicular to the model flight path. Results are presented as photographic time histories of the wake characteristics recorded with high speed still cameras. Effects of oscillation on the wake roll up are described in some detail, and the amount of vortex attenuation observed is discussed in comparative terms. Findings were consistent with flight test results in that only a small amount of rotation was observed in the wake for the asymmetric case. A possible aerodynamic mechanism contributing to this attenuation is suggested.

Jordan, Jr., F. L., McLemore, H. C. and Bragg, M. B.

"STATUS OF AERIAL APPLICATIONS RESEARCH IN THE LANGLEY VORTEX RESEARCH FACILITY AND THE LANGLEY FULL-SCALE WIND TUNNEL"

AIAA Paper No. 1978-1481, Los Angeles, CA, August 1978

The Langley Research Center is currently engaged in basic research to improve aerial applications technology. As part of this program, Langley's Vortex Research Facility and Full-Scale Wind Tunnel play lead roles in aircraft systems research to improve aircraft aerodynamics and dispersal systems efficiency, and in studies of aircraft wake-dispersal interactions to improve drift control and dispersal transport. In the Vortex Research Facility, small-scale models of agricultural airplanes are tested and numerical methods are utilized to study interactions between the airplane wake and the dispersed spray and granular materials. Methods are being developed to measure and predict dispersal transport and ground deposition with the objective of modifying wake characteristics and dispersal techniques to obtain interactions more favorable to wide, uniform deposition patterns and reduced drift. In the Full-Scale Wind Tunnel, full-scale agricultural airplanes and dispersal systems for both liquid and solid applications are evaluated to improve aircraft aerodynamics and dispersal systems efficiency. This paper presents the program status in these two facilities with emphasis on wake interactions and dispersal systems research.

Jordan, P. F.

"SPAN LOADING AND FORMATION OF WAKE"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 207-227

Classical analyses of aircraft wake formation assume that the wing span loading is (essentially) elliptic, and that in consequence the wake starts out being (essentially) flat. This assumption is incorrect: actual span loadings contain a logarithmic term, and in consequence there is an infinite upwash directly behind the wing just inside the wing tips. This explains why the aircraft wake rolls up faster than the classical analyses predict.

Jordan, P. F.

"STRUCTURE OF BETZ VORTEX CORES"

Journal of Aircraft, Vol. 10, No. 11, November 1973, pp. 691-693

In 1932 Betz proposed a principle of momentum conservation which leads to an unambiguous description of the structure of the major (the inviscid) part of the trailing vortex. In the present note, the analysis by which one calculates this structure for a wing with an arbitrary (but known) spanwise lift distribution is drastically simplified. Thus, an easier access is provided for discussions of questions like that of single versus multiple vortex pairs, of the effect of the detailed vortex structure on its stability, and such.

Joseph, R. M., Dasey, T. J. and Heinrichs, R. M.

"VORTEX AND METEOROLOGICAL MEASUREMENTS AT DALLAS/FT. WORTH AIRPORT"

AIAA Paper No. 1999-0760, Reno, NV, January 1999.

As part of NASA's Aircraft Vortex Spacing System (AVOSS), Lincoln Laboratory conducted meteorological and wake vortex data collection at Dallas/Ft. Worth (DFW) airport in 1997. A mobile continuous-wave coherent CO₂ laser radar was utilized to detect and track vortices generated by landing aircraft. Associated meteorological data were acquired by an extensive array of weather sensors. The DFW deployment is described here along with a preliminary analysis of vortex data. Vortex measurements from a 1995 lidar deployment in Memphis are also included in the analysis.

Josserand, Ch. and Rossi, M.

"THE MERGING OF TWO CO-ROTATING VORTICES: A NUMERICAL STUDY"

European Journal of Mechanics B/Fluids, Vol. 26, 2007, pp. 779-794

The merging of two-dimensional co-rotating vortices is analyzed through direct numerical simulations at large Reynolds numbers. It is shown how the Reynolds number affects each of the three phases that characterize this phenomenon. In the first phase, we examine the merging onset and focus on its definition. During the second rapid phase, the contributions of various flow regions upon the dynamics of a vortex are quantitatively studied. These regions are respectively the companion vortex, the filaments and an intermediate zone between vortices and filaments. The third phase is interpreted in terms of an advection diffusion process. Finally, the final profile and circulation of the merged vortex is determined: the two thirds of the total circulation of the two initial vortices is contained in the newly formed vortex.

Joubarne, E., Guibault, F., Braun, O. and Avellan, F.

"NUMERICAL CAPTURE OF WING TIP VORTEX IMPROVED BY MESH ADAPTATION"

International Journal for Numerical Methods in Fluids, Vol. 67, 2011, pp. 8-12.

This paper presents a mesh adaptation procedure linked to a finite volume solver, the goal of which is to increase the precision of the numerical simulation of a wing tip vortex flow. The adaptation scheme is applied to hexahedron meshes and hybrid meshes made up of tetrahedrons and prisms. To evaluate the ability of each type of element to capture the physics of a tip vortex, a specific test case is studied and results obtained numerically from this test case are compared with experimental results. The error estimator of the adaptation scheme is derived from a solution scalar variable. It is shown that the element anisotropy as well as the adaptation algorithms used have an impact on the precision of the solution. Adaptation of hexahedrons allows a better capture of the tip vortex far from the vortex root, even though the adaptation of those hexahedrons barely changes the number of nodes used to achieve a specified precision contrary to the adaptation of hybrid meshes.

Journade, J.

"NUMERICAL WAKE VORTEX CHARACTERIZATION"

AIAA Paper No. 2003-3815, Orlando, FL, June 2003

This paper deals with the achievements in wake characterization and prediction obtained at Airbus by means of a devoted computational tool based upon vortex particle methods. The code, called WaVES (Wake Vortex Extended Simulation), can be initialized either by an aircraft geometry (lifting surface model), or a load distribution or vorticity plane. It is capable of simulating wakes up to several tens of spans downstream, in 2D or 3D, with unsteady or stationary behaviors. To deal with long time computations, the 3D version has been implemented with several features. First a fast tree code approach has been developed to reach reasonable computational cost, a specific redistribution strategy is used which preserves the vortex sheet geometry, and an advancing frozen domain is used to save CPU time for stationary computations. Validation examples in 2D up to 50 spans and in 3D up to 10 spans illustrate the good behavior of the method.

Julien, S., Chomaz, J.-M. and Lasheras, J.-C.

"THREE-DIMENSIONAL STABILITY OF PERIODIC ARRAYS OF COUNTER-ROTATING VORTICES"

Physics of Fluids, Vol. 14, No. 2, February 2002, pp. 732-743

We study the temporally developing three-dimensional stability of a row of counter-rotating vortices defined by the exact solution of Euler's equations proposed by Mallier and Maslowe [Phys. Fluids 5, 1074 (1993)]. Based on the symmetries of the base state, the instability modes are classified in two types, symmetric and anti-symmetric. We show that the row is unstable to two-dimensional symmetric perturbations leading to the formation of a staggered array of counter-rotating vortices. For long wavelengths, the anti-symmetric mode is shown to exhibit a maximum amplification rate at small wave numbers whose wavelengths scale mainly with the period of the row. This mode could be interpreted as due to the Crow-type of instability extended to the case of a periodic array of vortices. For short wavelengths, symmetric and anti-symmetric instability modes are shown to have comparable growth rates, and the shorter the wavelength, the more complex the structure of the eigenmode. We show

that this short wavelength dynamic is due to the elliptic instability of the base flow vortices, and is well modeled by the asymptotic theory of Tsai and Widnall. The effect of varying the Reynolds number was also found to agree with theoretical predictions based on the elliptic instability.

Jumper, E. J. and Nelson, R. C.

"COMPUTING THE NEAR-FIELD DYNAMICS OF THE WAKE"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 95-104

The presentation will describe a modified discrete-vortex computational method developed at Notre Dame for computing the near-field dynamics of a wake issuing from a lift-producing wing. The method considers both the effect of the wing-bound, lift-producing circulation, and the fact that the wake (streamwise) vortices are not infinite but begin at the wing. The method uses the wing's spanwise load distribution as an input and computes the deformation and trajectory of the wake from its initial span-aligned geometry at the wing to its 'ultimate' wake geometry approximately four spans downstream from the wing. From this point, the dynamics of the full wake may continue to be computed; however, the presentation will describe our method of computing the continued wake dynamics with a simpler description of the wake. The criteria for determining how far downstream is sufficiently far to consider the geometric form of the wake to be its 'ultimate' form will also be discussed. A study using these computational methods of the wake produced by injecting additional discrete vortices into the wake at the wing will be described along with some of the conclusions drawn from the study.

Jun, L., Xuesong, W. and Tao, W.

"GLRT DETECTORS FOR AIRCRAFT WAKE VORTICES IN CLEAR AIR"

Chinese Journal of Aeronautics, Vol. 23, 2010, pp. 698-706.

In this article, radar echoes of aircraft wake vortices are modeled as weighted sums of the frequency components of the echoes with a special covariance matrix for the weighted coefficients. With a proposed detection scheme, two generalized likelihood ratio test (GLRT) detectors are derived respectively for aircraft wake vortices with time-varying and time-invariant Doppler spectra. Then the analytical expressions for detection and false alarm probabilities of the detectors are derived and three factors are investigated which mainly influence the detection performance, i.e., the Doppler extension and uncertainty of the aircraft wake vortex, and the number of the detection cells. The results indicate that, the signal-to-noise ratio (SNR) loss induced by Doppler extension is generally several decibels. The SNR loss due to Doppler uncertainty is approximately proportional to the logarithm of the number of spectrum lines in the uncertain Doppler spectrum intervals. For a large number of detection cells, the SNR gain is approximately proportional to the square root of the number of the detection cells.

Jung, J., Choi, W. and Lee, S.

"EFFECT OF THE BLADE INNER-TIP POSITION ON THE GENERATION OF TWIN VORTICES"

J. Aircraft, Vol. 45, No. 2, 2008, pp. 728-732

The effect of the chordwise inner-tip position was examined with conceptually designed blades that generate twin tip vortices. The three-dimensional Navier-Stokes solver HeliNA was used for flow field analysis. The trailing-tip blade showed higher performance and it was due to the lower sectional torque near the inner tip. Both blades generated a separated twin-vortex structure. The inner vortex of the trailing-tip blade was generated in a similar way to the conventional tip vortex, but that of the leading-tip blade was formed with a more distributed vorticity structure. The strength of the inner-tip vortex was weaker than the outer-tip vortex in hover. The difference of circulation between the inner and outer vortices was increased in the trailing-tip blade and was decreased in the leading-tip blade as thrust increased.

Jung, S. N., Sa, J. H., You, Y. H., Park, J. S. and Park, S. H.

"LOOSE FLUID-STRUCTURE COUPLED APPROACH FOR A ROTOR IN DESCENT INCORPORATING FUSELAGE EFFECTS"

Journal of Aircraft, Vol. 50, No. 4, July-August 2013, pp. 1016-1026.

A loose coupling approach is used to combine a comprehensive structural-dynamics code CAMRAD II and a computational fluid dynamics solver KFLOW to validate the data and to identify the effect of fuselage on the aeroelastic behavior of the second higher harmonic rotor acoustic test rotor. The computations are made using isolated rotor and rotor-fuselage models. To demonstrate the effect of a fuselage, the shaft tilt angles remain identical for both configurations. A good correlation has been obtained with the present computational fluid dynamics/comprehensive structural dynamics method. It is observed that a rotor-fuselage model improves the correlation significantly in terms of magnitudes and phases of the air loads solution. All the blade-vortex interaction peaks are captured accurately, and the phase shift in the section normal forces improves significantly, with the inclusion of a fuselage. The sources of improvements are investigated, considering the vorticity distributions and induced velocity fields of a rotor. It is revealed that the upwash pattern due to a fuselage is not restricted locally but propagates to considerable portion of the disk. Numerical results indicate that the upwash is responsible to lift up vortices at the zone of interest for a reduced miss distance, which results in a stronger blade-vortex interaction for improved correlations.

Jung, U. and Breitsamter, C.

"AERODYNAMIC WAKE INVESTIGATIONS OF HIGH-LIFT TRANSPORT AIRCRAFT WITH DEPLOYED SPOILERS"

ICAS Poster 2010-P2.25, September 2010, Nice, France.

Commercial Transport Aircraft (CTA) make use of spoilers in the approach phase. In doing so, the aerodynamic wake of the CTA's wing is highly influenced by the deployed spoilers, potentially leading to

horizontal tail plane (HTP) buffet. Mean and turbulent flow field quantities downstream of a CTA model's wing are investigated experimentally to evaluate the near field wake. The detailed half model features slats, aileron and flaps in high-lift approach configuration. Spoiler configurations comprise a baseline configuration with no spoilers deployed, a configuration with outboard conventional spoilers deployed 30 degrees, and two configurations, with two types of unconventional outboard spoilers. The experiments are performed in Wind Tunnel A at the Technical University of Munchen. Angles of attack are chosen for each configuration corresponding to a lift coefficient of 1.5. The freestream velocity is set to 50 m/s corresponding to a Reynolds number of 1,000,000. Two stream wise positions are chosen to evaluate the evolution of the wake from near the trailing edge of the wing to the tail of the model. Stereo Particle Image Velocimetry is used to measure the velocity distribution in the wake planes. At selected positions of the planes additional velocity measurements are taken by means of Constant Temperature Hot-Wire Anemometry. These time-resolved measurements serve to conduct a spectral analysis. It is shown that the wake of none of the three investigated spoiler configurations does impose a significant increase of vertical turbulence intensity on the HTP; neither broadband nor narrowband.

Jung, Y. and Seath, D. D.

"SPANWISE DISPLACEMENT OF A LINE VORTEX ABOVE A WING - A SIMPLE CALCULATION SCHEME"

Journal of Aircraft, Vol. 25, No. 5, May 1988, pp. 476-478

When a wing encounters a concentrated tip vortex, its aerodynamic characteristics are substantially altered due to nonlinear interaction. While the vortex affects the wing loads, the wing in turn affects the vortex path through its vorticity field. It is generally believed that some kind of iteration scheme is necessary to account for the mutual influence between the vortex and the wing trailing vorticity and, thus, to obtain an acceptable vortex path and its effect on induced air loads. The present method is based on the lifting line solution of the spanwise load distribution.

Jung, Y. W. and Park, S. O.

"VORTEX-SHEDDING CHARACTERISTICS IN THE WAKE OF AN OSCILLATING AIRFOIL AT LOW REYNOLDS NUMBER"

Journal of Fluids and Structures, Vol. 20, Issue 3, April 2005, pp. 451-464

An experimental investigation was carried out to study the unsteady characteristics of vortex shedding in the near wake of an oscillating airfoil. The airfoil was given a harmonic pitching motion about the quarter-chord axis at four reduced frequencies: 0.1, 0.2, 0.3, and 0.4. The mean incidence and the oscillating amplitude were 0 degrees and 3 degrees, respectively. The velocity in the wake was measured by hot-wire anemometry. Smoke-wire visualization was also carried out to investigate the link between the boundary layer flow and the shedding frequency variation. To analyze the frequency characteristics of the vortex shedding, we composed a short-time spectrum by the autoregressive (AR) method and a moving window. It was found that the shedding frequency in the wake of oscillating airfoil was much different from that for the case of steady airfoil at a given angle of attack, implying

that the state of the boundary layer dictated the vortex-shedding characteristics. The vortex-shedding frequency was found to vary with the phase angle of oscillation, not with the angle of attack, for a given reduced frequency. The range of variation of the shedding frequency was diminished as the reduced frequency of oscillation increased.

Jurdic, V., Joseph, P. and Antoni, J.

"INVESTIGATION OF ROTOR WAKE TURBULENCE THROUGH CYCLOSTATIONARY SPECTRAL ANALYSIS"

AIAA Journal, Vol. 47, No. 9, September 2009, pp. 2022-2030.

The present paper introduces cyclo-stationary spectral analysis as a new approach to analyze the turbulence velocity measurements generated by a rotor. To apply this technique, a random signal should have periodic statistical characteristics and should be suitable for many rotating mechanical systems as shown in recent studies. However, this method has never been applied on rotor velocity measurements. Via a Wigner-Ville representation, the instantaneous power spectra of the turbulence in the wakes and in between the wakes will be depicted and analyzed. The usefulness of the technique applied to rotor-generated turbulence is that it can separate the spectrum of the turbulence in between the wakes from that in the wake with a much greater frequency resolution than conventional spectral analysis.

Jurkovich, M. S. and Hummer, C. J.

"UNDERSTANDING THE FLOWFIELD BEHIND A TANKER AIRCRAFT"

AIAA Paper 2018-0536, January 2018, Kissimmee, FL.

The capabilities of the Kestrel flow solver with Cartesian off-body Adaptive Mesh Refinement are utilized in support of aerial refueling simulation with one aircraft in proximity behind another. Comparison to flight test data is used to demonstrate the achievable accuracy of Computational Fluid Dynamics (CFD) analysis for capturing the delta forces and moments on a tanker aircraft due to the proximity of a large receiver aircraft. The study also determined the set of options which minimize numeric dissipation in the vortex core, and tested resolving the wake vortex to the aft boundary of the computational domain. Best practices are proposed for utilizing CFD in tanker/receiver modeling while minimizing demand for computational resources.

Justus, C. G. and Johnson, D. L.

"THE NASA/MSFC GLOBAL REFERENCE ATMOSPHERIC MODEL: 1999 VERSION (GRAM-99)"

NASA TM-209630, May 1999, Marshall Space Flight Center; Huntsville, AL.

The latest version of Global Reference Atmospheric Model (GRAM-99) is presented and discussed. GRAM-99 uses either (binary) Global Upper Air Climatic Atlas (GUACA) or (ASCII) Global Gridded Upper Air Statistics (GGUAS) CD-ROM data sets, for 0-27 km altitudes. As with earlier versions, GRAM-99

provides complete geographical and altitude coverage for each month of the year. GRAM-99 uses a specially-developed data set, based on Middle Atmosphere Program (MAP) data, for 20-120 km altitudes, and NASA's 1999 version Marshall Engineering Thermosphere (MET-99) model for heights above 90 km. Fairing techniques assure smooth transition in overlap height ranges (20-27 km and 90-120 km). GRAM-99 includes water vapor and 11 other atmospheric constituents (O₃, N₂O, CO, CH₄, CO₂, N₂, O₂, O, A, He and H). A variable-scale perturbation model provides both large-scale (wave) and small-scale (stochastic) deviations from mean values for thermodynamic variables and horizontal and vertical wind components. The small-scale perturbation model includes improvements in representing intermittency ('patchiness'). A major new feature is an option to substitute Range Reference Atmosphere (RRA) data for conventional GRAM climatology when a trajectory passes sufficiently near any RRA site. A complete user's guide for running the program, plus sample input and output, is provided. An example is provided for how to incorporate GRAM-99 as subroutines in other programs (e.g., trajectory codes).

Justus, C. G., Jeffries III, W. R., Yung, S. P. and Johnson, D. L.

"THE NASA/MSFC GLOBAL REFERENCE ATMOSPHERIC MODEL-1995 VERSION (GRAM-95)"

NASA TM-4715, August 1995, Marshall Space Flight Center; Huntsville, AL.

The latest version of the Global Reference Atmospheric Model (GRAM-95) is presented and discussed. GRAM-95 uses the new Global Upper Air Climatic Atlas (GUACA) CD-ROM data set, for 0- to 27-km altitudes. As with earlier versions, GRAM-95 provides complete geographical and altitude coverage for each month of the year. Individual years 1985 to 1991 and a period-of-record (1980 to 1991) can be simulated for the GUACA height range. GRAM-95 uses a specially developed data set, based on Middle Atmosphere Program (MAP) data, for the 20- to 120-km height range, and the NASA Marshall Engineering Thermosphere (MET) model for heights above 90 km. Fairing techniques assure a smooth transition in the overlap height ranges (20 to 27 km and 90 to 120 km). In addition to the traditional GRAM variables of pressure, density, temperature and wind components, GRAM-95 now includes water vapor and 11 other atmospheric constituents (O₃, N₂O, CO, CH₄, CO₂, N₂, O₂, O, A, He, and H). A new, variable-scale perturbation model provides both large-scale and small-scale deviations from mean values for the thermodynamic variables and horizontal and vertical wind components. The perturbation model includes new features that simulate intermittency (patchiness) in turbulence and small-scale perturbation fields. The density perturbations and density gradients (density shears) computed by the new model compare favorably in their statistical characteristics with observed density perturbations and density shears from 32 space shuttle reentry profiles. GRAM-95 provides considerable improvement in wind estimates from the new GUACA data set, compared to winds calculated from the geostrophic wind relations previously used in the 0- to 25-km height range. The GRAM-95 code has been put into a more modular form, easier to incorporate as subroutines in other programs (e.g., trajectory codes). A complete user's guide for running the program, plus sample input and output, is provided.

Kaarlonen, K. and Laine, S.

"THE EFFECT OF THE REYNOLDS NUMBER ON THE WING VORTICES"

ICAS-2002-2.2.2, Toronto, Canada, September 2002

Wind tunnel experiments have shown that the vortex system of a delta-wing configuration with rounded leading edges, ELAC-1, depends on the Reynolds number. The purpose of this study was to examine the Reynolds number effect by using a Navier-Stokes flow solver with two advanced turbulence models, an explicit algebraic Reynolds stress model and a kappa-omega SST model.

Kaden, A. and Luckner, R.

"MODELING WAKE VORTEX ROLL-UP AND VORTEX-INDUCED FORCES AND MOMENTS FOR TIGHT FORMATION FLIGHT"

AIAA Paper 2013-5076, August 2013, Boston, MA.

Migratory birds that fly in tight formation use the upwash of the leading birds to save energy. Aircraft can use the same principle to save fuel. To date, commercial aircraft do not fly in tight formation because of unresolved technical and operational issues. However, increasing fuel cost and environmental constraints are drivers to investigate tight formation flight and the potential fuel savings. For such investigations a good knowledge of the vortex-induced velocities and the effect on the encountering aircraft is fundamental. In research on safe separation distances the vortex far field (more than 40 wingspans behind the generating aircraft) is modeled with a pair of straight vortices. This paper addresses a method to model the wake vortex roll-up that occurs in the near field (up to 15 wingspans behind the generating aircraft) using discrete vortex filaments. The motion of these filaments due to the mutual velocity induction is simulated numerically, followed by the calculation of the resulting induced velocities in a second step. To find an appropriate set of simulation parameters, the computed velocities are compared with those induced by a validated wake vortex velocity model. An already existing wake vortex encounter simulation software is improved to model the wake vortex roll-up. First simulation results are presented.

Kadlec, P. W.

"FLIGHT DATA ANALYSIS OF THE RELATIONSHIP BETWEEN ATMOSPHERIC TEMPERATURE CHANGE AND CLEAR AIR TURBULENCE"

AMS/AIAA Paper No. 66-365, March 1966, Los Angeles, CA.

To determine what atmospheric temperature changes can be used to detect clear air turbulence at jet altitudes, data were collected during one year on 146 flights by riding as an extra crew member in the cockpit of airline and military jet aircraft. In addition, an aircraft flight data recorder and air data system on one DC-8 were modified to collect static air temperature information using an improved temperature sensor. From flight observations using a portable temperature change instrument and the flight recorder data, a rate of temperature change of 1.0 deg C per minute was found to be the most useful criterion for correctly indicating clear air turbulence. Since the inception of manned flight in

powered aircraft, the rapid and constant advance in the performance capabilities of airplanes has forced the aeronautical meteorologist to develop new concepts of atmospheric behavior. The current stage in the evolution of flight is dominated by jet aircraft, traveling near the speed of sound at altitudes above 25,000 feet. With the rapidly expanding numbers of operational jet aircraft and the associated increased frequency of pilot reports of CAT encounters, research meteorologists have become concerned with the relationship of clear air turbulence to specific synoptic features in the atmosphere. Although forecasting techniques have greatly improved, the predicted geographical areas and vertical depths of CAT remain too extensive. Atmospheric soundings normally taken only once every 12 hours by the rather widely separated stations of the radiosonde network, impose basic limitations on the degree of forecasting skill that may be developed. Therefore, in order to pinpoint an area of turbulence with greater accuracy, an airborne instrument is needed to warn of the proximity of Cat in much the same manner that radar warns the pilot of thunderstorms. Ideally, the prospect of an airborne device which could probe ahead of a moving aircraft and detect areas of clear air turbulence would be the most practical method of avoiding it. Such a device, used in conjunction with the turbulence forecast, would enable jet flight crews to avoid or minimize the discomfort and possible hazard which Cat now imposes.

Kadygrov, E. N., Koldaev, A. V., Viazankin, A. S., Argentini, A. and Conidi, A.

"A NEW MICROWAVE TEMPERATURE PROFILER -- FIRST MEASUREMENTS IN POLAR REGIONS"

Thirteenth ARM Science Team Meeting Proceedings, April 2003, Broomfield, CO.

Temperature inversions are a ubiquitous feature of the high latitude atmospheric boundary layer (ABL). In Polar Regions, the temperature inversion is a complicated phenomenon involving interactions between surface radiative cooling, subsidence, and warm air advection. In the period 1997-2002, several microwave temperature profilers were used to measure temperature inversion parameters at one of the three sites of the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program, located at the North Slope of Alaska (NSA). These instruments provided continuous, unattended observation of the ABL thermal structure. However, the vertical resolution was not large enough to measure the low-level lifted inversions, which were observed in the spring period by radiosondes. In 2001, the Russian scientific production company ATTEX, in cooperation with the Dutch Company Kipp and Zonen, produced a new microwave temperature profiler for Polar regions, MTP-5P (P stands for Polar), with improved vertical resolution.

Kaikwong, H. and Pakwai, C.

"AIRCRAFT WAKE VORTEX OBSERVATIONS IN HONG KONG"

Journal of Radars, Vol. 6, 2017, pp. 1-10.

The Hong Kong International Airport (HKIA) is among the busiest airports in the world, with total aircraft movements exceeding 400,000 in 2016. The Hong Kong Observatory (HKO), provider of aviation meteorological services to HKIA, has recently begun making the first sets of aircraft wake

vortex observations at HKIA using short-range LIDARs. This paper briefly describes the preliminary observation results obtained from field measurements between 2014 and 2016, and discusses the way forward on the monitoring and prediction of wake vortex behavior in Hong Kong.

Kakimoto, I., Harada, T., Kameyama, S., Ha, J.-S. and Kim, H.-I.

"UP TO 12 KM VERTICAL WIND PROFILING USING MITSUBISHI ELECTRIC'S LONG RANGE LIDAR"

19th Coherent Laser Radar Conference (CLRC), Paper P31, June 2018, Okinawa, Japan.

A new function of Mitsubishi Electric's long range lidar for vertical wind profiling has been developed. The observation performance evaluation was carried out by KARI, and the result shows that the measurable height of up to 12 km in no precipitation condition was demonstrated. The correlation coefficient of wind speed and direction between the lidar and radio sonde are also shown. The result implies the expanding use of wind lidars for high altitude wind sensing.

Kalkhoran, I. M.

"VORTEX DISTORTION DURING VORTEX-SURFACE INTERACTION IN A MACH 3 STREAM"

AIAA Paper No. 93-0761, January 1993, Reno, NV.

An experimental study has been conducted in a Mach 3 stream to investigate supersonic vortex behavior upon interacting with a solid lifting surface placed in its passage. The experimental scheme involved positioning a two-dimensional wedge surface downstream of a slender semi-span vortex-generator wing section such that the generated trailing tip vortices interacted with the downstream wedge surface. The experimental setup was arranged so that interactions resulted in a close encounter of the vortex core and the wedge leading edge. Spark shadow photographs of the flow field along with chord-wise pressure measurements on the wedge surface were used to study the interaction problem. In their most organized form, distortion of stream-wise vortices upon interacting with the surface was found to result in formation of unsteady detached shock fronts followed by an apparent slip surface separating a subsonic region from a supersonic zone. The interaction was found to depend strongly on vortex strength and vortex proximity to the wedge leading edge and the generated flow field was found to be highly unsteady.

Kalkhoran, I. M.

"EXPERIMENTAL INVESTIGATION OF THREE-DIMENSIONAL VORTEX-AIRFOIL INTERACTION IN A SUPERSONIC STREAM"

Poly-AE 95-3, July 1995, Polytechnic University, Brooklyn, NY.

An experimental study of the interaction between stream-wise vortices and a two-dimensional surface was conducted in a Mach 2.5 flow. The influence of oblique shock wave intensity on the inherently three-dimensional interaction was examined for vortices of variable strength. Planar laser

sheet visualizations of the flow field generated by the interaction at several distances downstream of the wedge leading edge were performed to gain an understanding of vortex behavior at distances further downstream. Results indicated that the interaction of a moderate strength vortex with an oblique shock wave leads to the formation of a steady separated shock structure upstream of the oblique shock front. Planar laser sheet visualization of the flow field revealed an expansion of the vortex core in crossing a strong oblique shock front. The vortical structure was observed to persist along the entire chord of the shock generating wedge but was seen to diffuse with distances downstream of the wedge leading edge. Measurements of the vortex center above the wedge surface indicated that immediately downstream of the normal portion of the bulged-forward shock wave the vortex center was parallel to the direction of the free stream flow.

Kalkhoran, I. M.

"VORTEX DISTORTION DURING VORTEX-SURFACE INTERACTION IN A MACH 3 STREAM"

AIAA Journal, Vol. 32, No. 1, January 1994, pp. 121-129.

An experimental study has been conducted in a Mach 3 wind tunnel to investigate the behavior of supersonic vortices as they interact with a wedge surface placed in their passage. The experimental setup was arranged so that interactions resulted in a close encounter of the vortex core and the wedge leading edge. Spark shadow photographs of the flow field along with pressure measurements on the wedge surface were used to study the interaction problem. In their most organized form, distortion of streamwise vortices upon interacting with the wedge was found to result in formation of symmetric detached shock fronts far upstream of the wedge leading edge followed by an apparent slip surface separating a subsonic region from a supersonic zone. Interaction experiments leading to substantial changes in the structure of vortices revealed that the supersonic vortex distortion has strong resemblances to the incompressible 'B-breakdown' reported in the literature. Experimental results also indicate that the interaction strongly depends on the vortex strength and vortex proximity to the wedge leading edge, and the generated flow field was found to be highly unsteady. Interaction of concentrated streamwise vortices with the oblique shock formed over the wedge surface resulted in formation of a locally three-dimensional shock wave with a limited subsonic region downstream of the shock.

Kalkhoran, I. M.

"AN EXPERIMENTAL INVESTIGATION OF THE PERPENDICULAR VORTEX-AIRFOIL INTERACTION AT TRANSONIC SPEEDS"

PhD Thesis, Univ. of Texas, Arlington, TX, 1987

Extensive experimental studies were conducted in the UTA High Reynolds Number Transonic Wind Tunnel facility. Experimental investigations of the compressible trailing vortex system were performed by means of a thorough probing of the viscous core of the vortex system. Detailed flow field measurements and contour plots of the total pressure field in the neighborhood of the vortex core are presented. Comprehensive experimental studies were conducted to investigate the pressure

distribution on a C141 and a NACA 0012 airfoil sections for a range of transonic flow conditions. Transonic vortex airfoil interaction tests at Mach numbers ranging from 0.68-0.90 and airfoil chord Reynolds numbers of 3.5-6 million were conducted to simulate the helicopter rotor blade vortex interaction problem. The interaction scheme involves positioning a lifting wing (vortex generator) upstream of an airfoil so that the trailing vortex interacts with the downstream airfoil. The interacting airfoils included a symmetric NACA 0012 and a two-dimensional C-141 (NACA 65 series) airfoil section. The effects of vortex strength, vortex height above the downstream airfoil, Mach number and Reynolds number on the pressure distribution of the downstream airfoil, and the normal force coefficients were studied and the quantitative results are presented. The results obtained from these experiments indicate a substantial change in the pressure distribution of the downstream airfoil, a spanwise drift of the vortex core after interacting with the airfoil, and a high degree of unsteadiness in the vicinity of the vortex viscous core.

Kalkhoran, I. M. and Paek, C.

"EXPERIMENTAL STUDY OF A WEAK VORTEX-NORMAL SHOCK INTERACTION"

AIAA Journal, Vol. 42, No. 6, 2004, pp. 1264-1267

To expand upon the results of previous normal shock wave-vortex interaction studies, an experimental investigation of the interaction between a weak vortex and an otherwise normal shock wave was carried out in a Mach 2.49 flow. Measurements of the flow properties in the core region of the weak vortex indicated reduced total pressures, a wakelike axial Mach-number distribution, and a Burgers-like swirl profile. These parameters contained identical trends to those measured for moderate and strong vortices but with much lower intensities. These measurements further revealed a significant reduction of the axial Mach number in the vortex generator wake where the measured axial Mach number was seen to be lower than that at the vortex axis. Interaction of the weak vortex with a normal shock front revealed a local bulging of the shock wave in the upstream direction. The upstream bulging of the shock wave was seen to be more pronounced in the wake region where the Mach number was a minimum. Examination of the generated flow field did not reveal a vortex distortion pattern comparable to the supersonic vortex breakdown observed during previous shock wave-vortex interaction studies.

Kalkhoran, I. M. and Sforza, P. M.

"AIRFOIL PRESSURE MEASUREMENTS DURING OBLIQUE SHOCK WAVE-VORTEX INTERACTION IN A MACH 3 STREAM"

AIAA Paper No. 1992-2631, June 1992, Palo Alto, CA.

An experimental investigation of the interaction of discrete vortices and oblique shock waves was conducted in a Mach 3 blowdown wind tunnel. An instrumented two-dimensional wedge airfoil section was placed downstream of a semi-span wing section so that the trailing tip vortex would interact with the shock wave formed over the downstream test airfoil. The experiments were designed to simulate

interaction of streamwise vortices from upstream sections with shock waves formed over aft surfaces as might be encountered in supersonic flight of aircraft and missiles. The influence of vortex strength and vortex-airfoil vertical separation distance on the interaction was examined. The flow field generated was found to be highly unsteady and a substantial change in the pressure distribution of the downstream airfoil was observed. Furthermore, the interaction of strong vortices with the oblique shock waves over the test airfoil resulted in formation of unsteady shock waves far upstream of the airfoil leading edge.

Kalkhoran, I. M. and Sforza, P. M.

"AIRFOIL PRESSURE MEASUREMENTS DURING OBLIQUE SHOCK-WAVE/VORTEX INTERACTION IN A MACH 3 STREAM"

AIAA Journal, Vol. 32, No. 4, April 1994, pp. 783-788

An experimental investigation of the interaction between stream-wise discrete vortices and oblique shocks formed over a two-dimensional wedge surface was conducted in a Mach 3 blowdown wind tunnel. An instrumented two-dimensional wedge section was placed downstream of a semispan wing so that the trailing tip vortex would arbitrarily interact with the shock wave formed over the wedge surface. The experiments were designed to simulate interaction of streamwise vortices from upstream bodies with shock waves formed over aft surfaces as might be encountered in supersonic flight of aircraft and missiles. The influence of vortex strength and vortex-airfoil vertical separation distance on the interaction was examined. The flow field generated was found to be highly unsteady, and a substantial change in the pressure distribution on the downstream airfoil was observed. The interaction of a strong vortex with the oblique shock wave over the downstream wedge section resulted in formation of an unsteady detached shock wave upstream of the wedge leading edge. Furthermore, when the vortex approached the wedge leading edge, formation of a detached shock wave occurred further upstream of the section leading edge.

Kalkhoran, I. M. and Smart, M. K.

"ASPECTS OF SHOCK WAVE-INDUCED VORTEX BREAKDOWN"

Progress in Aerospace Sciences, Vol. 36, 2000, pp. 63-95

In this article, we discuss supersonic vortex breakdown when sufficiently strong streamwise vortices encounter otherwise planar, normal and oblique shock fronts as well as solid surfaces placed in their passages. The dramatic destruction of a streamwise vortex during supersonic vortex interactions reveals a vortex breakdown similar in many ways to the well-documented incompressible vortex bursting. The main features of supersonic vortex breakdown include formation of a spherically blunt-nosed conical shock, and a vortex core, which upon crossing the apex of the conical shock expands into a subsonic turbulent conical region. A notable characteristic of the supersonic vortex breakdown is the formation of an entropy-shear layer separating an inner subsonic zone containing the burst structure from the surrounding supersonic flow. Numerical, experimental, and analytical studies of shock

wave/vortex interactions are discussed and results from wind tunnel studies involving head-on collision of supersonic vortices with solid surfaces are presented.

Kalkhoran, I. M. and Smart, M. K.

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Kalkhoran, I. M., Sforza, P. M. and Wang, F. Y.

"EXPERIMENTAL STUDY OF SHOCK-VORTEX INTERACTION IN A MACH 3 STREAM"

AIAA Paper No. 1991-3270, September 1991, Baltimore, MD.

An experimental investigation of interactions between tip vortices and shock waves of various strength was conducted in the Mach 3 blowdown supersonic wind tunnel at Polytechnic University. The interaction scheme involved positioning a shock wave generator upstream of a semispan wing vortex generator such that tip vortices generated from the lifting surface arbitrarily interacted with shock waves. The resulting interaction was found to be highly unsteady and the observed structure of the flow varied appreciably with shock wave strength. For the case of tip vortices intersecting bow shock waves in front of blunt bodies, formation of conical shock waves were observed.

Kalkhoran, I. M., Smart, M. K. and Betti, A.

"INTERACTION OF SUPERSONIC WING TIP VORTICES WITH A NORMAL SHOCK"

AIAA Paper No. 1995-2283, San Diego, CA, June 1995

An experimental study involving interaction of concentrated streamwise wing tip vortices and normal shock fronts was carried out in a Mach 2.49 flow. The interaction scheme involved positioning a vortex-generator wing section upstream of a pilot-type normal shock inlet such that the wing tip vortices interacted with the normal shock formed in front of the inlet. The vortex strength was varied by

placing the vortex generator wing at different angles of attack while a normal shock was created by adjusting the mass flow rate passing through the inlet. Spark shadowgraphs, laser sheet planar visualizations, and pitot pressure measurements of the flow field indicated a significant change in the structure of streamwise vortices generated by the vortex generator wing at 5 and 10 deg angle of attack upon encountering a normal shock discontinuity. Results of the investigation showed that the interactions lead to the formation of an unsteady conical shock wave far upstream of the inlet as well as a highly turbulent flow downstream for both vortices. Pitot pressure measurements using a fast response pressure transducer in conjunction with the spark shadowgraphs revealed a bimodal feature of the flow field. The frequency of oscillation of the generated structure was found to be higher for increased vortex strength.

Kalkhoran, I. M., Smart, M. K. and Betti, A.

"INTERACTION OF SUPERSONIC WING-TIP VORTICES WITH A NORMAL SHOCK"

AIAA Journal, Vol. 34, No. 9, Sept. 1996, pp. 1855-1861.

An experimental study involving interaction of concentrated streamwise wing-tip vortices and normal shock fronts was carried out in a Mach 2.49 flow. The interaction scheme involved positioning a vortex-generator wing section upstream of a pitot-type normal shock inlet such that the wing-tip vortices interacted with the normal shock formed in front of the inlet. The vortex strength was varied by placing the vortex generator wing at different angles of attack while a normal shock was created by adjusting the mass flow rate passing through the inlet. Spark shadowgraphs, laser sheet planar visualizations, and pitot pressure measurements of the flow field indicated a significant change in the structure of streamwise vortices generated by the vortex generator wing at 5.7- and 10.4-deg angle of attack upon encountering a normal shock discontinuity. Results of the investigation showed that the interactions lead to the formation of an unsteady conical shock wave far upstream of the inlet as well as a highly turbulent flow downstream for both vortices. Pitot pressure measurements using a fast response pressure transducer in conjunction with the spark shadowgraphs revealed a bimodal feature of the flow field. The frequency of oscillation of the generated structure was found to be higher for increased vortex strength. Measurements of pitot pressure in the vortex core in the absence of a shock wave revealed high-frequency oscillations that were attributed to the vortex meandering phenomenon.

Kalkhoran, I. M., Smart, M. K. and Popovic, S.

"PLANAR LASER SHEET VISUALIZATION OF OBLIQUE SHOCK WAVE/VORTEX INTERACTION"

AIAA Paper No. 96-0046, Jan. 1996, Reno, NV.

Planar laser sheet visualizations of the flow field generated by the interaction of a streamwise wing tip vortex and a strong oblique shock front at several distances downstream of a shock generating wedge were performed in a Mach 2.49 flow. The experimental scheme involved positioning a two-dimensional wedge surface downstream of a vortex generator wing section so that the wing-tip vortex interacts with the planar oblique shock front. The results of the investigation revealed an expansion of

the vortex core in crossing a strong oblique shock front. The maximum vortex core diameter was seen to occur at a distance of 12.7 mm downstream of the wedge leading edge while at distances further downstream, the vortex core diameter remained approximately constant. The vortical structure was observed to persist along the entire chord of the shock generating wedge but was seen to diffuse with distances downstream of the wedge leading edge. Measurements of the vortex position relative to the wedge surface indicated that immediately downstream of the normal portion of a bulged-forward shock wave, the vortex axis was parallel to the direction of the freestream flow. On the other hand, the vortex was observed to travel parallel to the wedge surface at distances downstream of the wedge mid-chord position. The conical structure which forms as a result of vortex distortion was found to be sensitive to downstream disturbances in a manner similar to the incompressible vortex breakdown.

Kalkhoran, I. M., Smart, M. K. and Wang, F. Y.

"SUPERSONIC VORTEX BREAKDOWN DURING VORTEX/CYLINDER INTERACTION"

J. Fluid Mech., Vol. 369, March 1998, pp. 351-380

The head-on interaction of a supersonic streamwise vortex with a circular cylinder reveals a vortex breakdown similar in many ways to that of incompressible vortex breakdown. In particular, the dramatic flow reorganization observed during the interaction resembles the conical vortex breakdown reported by Sarpkaya (1995) at high Reynolds number. In the present study, vortex breakdown is brought about when moderate and strong streamwise vortices encounter the bow shock in front of a circular cylinder at Mach 2.49. The main features of the vortex/cylinder interaction are the formation of a blunt-nosed conical shock with apex far upstream of the undisturbed shock stand-off distance, and a vortex core which responds to passage through the apex of the conical shock by expanding into a turbulent conical flow structure. The geometry of the expanding vortex core as well as the location of the conical shock apex are seen to be strong functions of the incoming vortex strength and the cylinder diameter. A salient feature of the supersonic vortex breakdown is the formation of an entropy-shear layer, which separates an interior subsonic zone containing the burst vortex from the surrounding supersonic flow. In keeping with the well-established characteristics of the low-speed vortex breakdown, a region of reversed flow is observed inside the turbulent subsonic zone.

Kalkhoran, I. M., Wang, F. Y., Milanovic, I. and Smart, M. K.

"SUPERSONIC VORTEX BREAKDOWN DURING VORTEX/CYLINDER INTERACTION"

1997 ASME Fluids Engineering Division Summer Meeting, June 1997

An experimental study involving the interaction between streamwise vortices of various strength with circular cylinders in a supersonic stream has been carried out. The interaction scheme involved positioning a vortex-generator wing section upstream of a circular cylinder such that the wing-tip vortices interacted with the cylinder. Spark shadowgraphs, surface oil visualization, pitot and static pressure measurements of the flow field indicated a significant change in the structure of streamwise vortices because of the encounter. The vortex/cylinder interaction experiments lead to formation of a

highly turbulent conical structure surrounded by a conical shock wave far upstream of the interacting cylinder. The scale of the conical structure containing the burst vortex as well as the intensity of interaction leading to vortex breakdown are seen to be strong functions of the vortex strength. Like the well-established characteristics of incompressible vortex breakdown, a region of reversed flow and formation of stagnation points are observed inside of the highly turbulent conical region. Interaction experiments leading to vortex breakdown are seen to have many characteristics of supersonic vortex distortion observed during normal shock wave/vortex interaction with one notable exception i.e., the generated flow field is seen to be globally steady during the present study. The significant upstream influence observed during the interaction is a unique feature of supersonic vortex breakdown partly due to wake-like axial Mach number distribution in the vortex core and its streamwise evolution. The extent of the burst structure and the scale of the conical shock were found to depend on the cylinder size indicating a strong influence of the downstream boundary on supersonic vortex breakdown.

Kalkhoran, I. M., Wilson, D. R. and Seath, D. D.

"EXPERIMENTAL INVESTIGATION OF THE PERPENDICULAR ROTOR BLADE-VORTEX INTERACTION AT TRANSONIC SPEEDS"

AIAA Journal, Vol. 30, No. 3, March 1992, pp. 747-755.

Transonic perpendicular rotor blade-vortex interaction tests at Mach numbers ranging from 0.68 to 0.9 and Reynolds numbers (based on airfoil chord) of 3.8-5.5 million were conducted in the UTA high-Reynolds number, transonic Ludwig-tube wind tunnel. The scheme involved positioning a lifting wing (vortex generator) upstream of an instrumented NACA 0012 airfoil so that the trailing vortex interacted with the downstream airfoil. Tests were performed at several vortex strengths as well as several vortex core heights above the downstream airfoil. The results obtained from these experiments indicate that a substantial change in the pressure distribution of the downstream airfoil occurs, but most of the effects were confined to the leading 30 percent of the airfoil chord. A spanwise drift of the vortex core as it passes over the trailing airfoil, similar to results obtained previously in low-speed wind tunnel tests, as well as a high degree of unsteadiness in the vicinity of the vortex center were observed.

Kalogiros, J. A. and Wang, Q.

"AERODYNAMIC EFFECTS ON WIND TURBULENCE MEASUREMENTS WITH RESEARCH AIRCRAFT"

Journal of Atmospheric and Oceanic Technology, Vol. 19, October 2002, pp. 1567-1576.

Flow distortion is a major issue in the measurement of wind turbulence with gust probes mounted on a nose boom, at the radome, or under the wing of research aircraft. In this paper, the effects of both propellers of a turboprop aircraft and of the aircraft vortex system on the pressure and wind velocity measurements near the nose of the aircraft are examined. It is shown that, for a turboprop aircraft, the sensors mounted near the nose are affected directly (slipstream) or indirectly (lift increase) by the propellers. The propeller effects are more significant for pressure sensors located ahead of the propellers on the fuselage and are less significant for the small local flow angles measured at the nose

of the aircraft. The first case is clearly realized during in-flight calibration maneuvers performed by a turboprop aircraft. A major flow distortion, which seriously affects the vertical wind velocity measurements near the nose of an aircraft, is the upwash induced mainly by the wing-bound vortex. Also, low energy of the vertical wind component in the inertial subrange for scales larger than the fuselage diameter is usually observed in aircraft measurements. This is shown to be the result of not considering the decrease of the upwash correction with eddy frequency (or no need for such a correction in the inertial subrange) caused by the aerodynamic delay and the response of the wing vortex to turbulence. The level of energy in the inertial subrange of the vertical wind component is significant because it is commonly used for the estimation of the dissipation rate of turbulence kinetic energy. A method to estimate this frequency variable correction and correct the spectra or the time series of the estimated vertical wind component is described. Data from low-level flight legs with a Twin Otter aircraft show that this correction may result in about a 20 percent correction of the variance of the vertical wind component and a 5 percent correction of the vertical turbulent fluxes.

Kalra, T. S. and Baeder, J. D.

"MODELING SUBSCALE ROTOR WAKE IN GROUND EFFECT WITH ACCURATE TURBULENT LENGTH SCALES"

AIAA Journal, Vol. 55, No. 9, September 2017, pp. 3085-3094.

An accurate prediction of the tip vortex flow field is required to understand the viscous interaction of the rotor wake and ground prevalent during helicopter brownout. To achieve this goal, a compressible, structured, overset Reynolds-averaged Navier-Stokes-based solver is used to simulate a subscale rotor in ground effect. Novel mesh-gridding techniques are used to avoid prohibitive computational costs. The Reynolds-averaged Navier-Stokes equations solved with the Spalart-Allmaras turbulence model show that a smeared-out flow field at an early wake, ages due to excessive turbulence levels. To further investigate that the source of a smeared rotor wake is the use of turbulence modeling, the computations are performed with laminar flow assumption that show a preserved rotor wake field for longer wake ages. However, an accurate understanding of the cause of brownout requires an accurate prediction of turbulence levels. Therefore, a hybrid Reynolds-averaged Navier-Stokes/large-eddy simulation methodology such as delayed detached-eddy simulation is explored. The flow field obtained from the delayed detached-eddy simulation methodology still does preserve the rotor wake. Because the wake capturing grids are highly anisotropic, a modified length scaling is used. The delayed detached-eddy simulation-based length scale with correction for anisotropic grids helps in preserving the rotor wake and shows a close agreement with experimental results.

Kalvig, S., Maanger, E. and Hjertager, B.

"COMPARING DIFFERENT CFD WIND TURBINE MODELLING APPROACHES WITH WIND TUNNEL MEASUREMENTS"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012056-1 - 012056-13.

The performance of a model wind turbine is simulated with three different CFD methods: actuator disk, actuator line and a fully resolved rotor. The simulations are compared with each other and with measurements from a wind tunnel experiment. The actuator disk is the least accurate and most cost-efficient, and the fully resolved rotor is the most accurate and least cost-efficient. The actuator line method is believed to lie in between the two ends of the scale. The fully resolved rotor produces superior wake velocity results compared to the actuator models. On average it also produces better results for the force predictions, although the actuator line method had a slightly better match for the design tip speed. The open source CFD tool box, OpenFOAM, was used for the actuator disk and actuator line calculations, whereas the market leading commercial CFD code, ANSYS/FLUENT, was used for the fully resolved rotor approach.

Kalyadina, T. V. and Morozov, V. V.

"COMPUTING THE DANGER ZONE RADIUS AROUND A VORTEX"

Computational Math. and Modeling, Vol. 14, No. 4, 2003, pp. 402-409. [Translated from Prikladnaya Matematika I Informatika, No. 12, 2002, pp. 71-79.]

We consider an optimization problem associated with aircraft flight safety. A bound on the second derivative of the objective function is derived. In some cases, this bound analytically produces the optimal value of the objective function and reduces the computations required for simulation of vortices separating from the wings of passing aircraft.

Kamali, C., Pashilkar, A., Indira, N., Goyal, A., Premalatha, and Mudkavi, V.

"MODELING AND SIMULATION OF WAKE ENCOUNTER FOR A FIGHTER AIRCRAFT"

International Journal of Aerospace Innovations, Vol. 4, Number 3 and 4, 2012, pp. 65-74.

This paper addresses the development of six degrees of freedom model for simulation of flight in the wake of a similar class aircraft. The aircraft considered in this study is a high-performance fighter with full authority flight control laws. Apart from the aerodynamic effects, the flight dynamic model also includes a model of the air data system and the feedback control laws. The model is used to study the effect of wake on the flight dynamic response of the aircraft with and without effect of wake on the air data system feedback variables like angle of attack, angle of sideslip and static pressure.

Kamari, D. and Tadjfar, M.

"INFLUENCE OF TIP SHAPE ON STRUCTURE OF WING-TIP VORTEX AT LOW REYNOLDS NUMBERS"

Proceedings ASME 2009 Fluids Engineering Division Summer Meeting, FEDSM2009-78230, August 2009, Vail, CO.

An important phenomenon in three-dimensional flow over a wing is the existence of wingtip vortices. It has significant effects on the aerodynamics of flying vehicles. In this computational study, we

investigate the effects of geometry of the wingtip on the structure of the wing-tip vortices. Here, we consider a rectangular half-wing with NACA0012 airfoil as cross section. The aerodynamic coefficients and the flow-field variables are computed at low Reynolds numbers below 50,000. As the edge-shape parameter is increased the wing tip vortex is weakened. This influence is higher at higher values of Reynolds number. But, the increase of angle of attack does not change the shape or rate of this increase.

Kambe, T.

"VORTEX SOUND WITH SPECIAL REFERENCE TO VORTEX RINGS; THEORY, COMPUTER SIMULATIONS, AND EXPERIMENTS"

Aeroacoustics, Vol. 9, Nos. 1 and 2, 2010, pp. 51-89.

This is a review paper on vortex sound with special reference to vortex rings and sound emission detected in experimental tests. Any unsteady vortex motion excites acoustic waves. From the fundamental conservation equations of mass, momentum, and energy of fluid flows, one can derive a wave equation of aerodynamic sound. The wave equation of acoustic pressure can be reduced to a compact form, called the equation of vortex sound. This equation predicts sound generation by unsteady vortex motions. On the other hand, based on the matched asymptotic expansion (using the multipole expansions), one can derive a formula of wave pressure excited by time-dependent vorticity field localized in space. The theoretical predictions are compared with experimental observations and direct computer simulations. The systems considered are, head-on collision or oblique collision of two vortex rings, vortex-cylinder interaction, vortex-edge interaction, and others. Scaling laws of the pressure of emitted sound are predicted by the theory and compared with experimental observations. Comparison between theories and observations shows excellence of the theoretical predictions. Direct numerical simulations are reviewed briefly for sound generation by collisions of two vortex rings and that by a cylinder immersed in a uniform stream (aeolian tones). Vortex sound in superfluid is also reviewed about experimental observations and computational studies on the basis of the Gross-Pitaevski equation.

Kambe, T. and Minota, T.

"SOUND RADIATION FROM VORTEX SYSTEMS"

Journal of Sound and Vibration, Vol. 74, No. 1, 1981, pp. 61-72.

Sound radiation from a localized, weakly compressible flow in an inviscid fluid is investigated. A matching method enables the surrounding acoustic field to be related to the local eddy flow associated with a system of compact vortices. By using an asymptotic expansion of the velocity potential associated with the vorticity distribution, a general expression for the acoustic pressure is found to depend linearly on the vorticity, in accord with the theories of Mohring and Obermeier. This scheme is applied to an interacting system of coaxial circular vortex rings, and in particular two examples are

presented of the time histories of the radiated acoustic pressures which are generated by interactions of two identical vortex rings, in 'head-on collision' and in 'mutual threading' respectively.

Kambe, T. and Oo, U. M.

"SCATTERING OF SOUND BY A VORTEX RING"

Journal of the Physical Society of Japan, Vol. 50, No. 10, October 1981, pp. 3507-3516

Following the theory of aerodynamic sound scattering, a general formula of the scattered sound pressure is presented for a case of a plane harmonic wave incident upon a flow field localized in space. The expression is valid even when the flow is time-dependent and applied to the scattering by a vortex ring in translational motion. The scattering amplitude and cross-section are determined numerically under the condition of slow motion. They depend not only on the incident wavelength, but also on the direction of the vortex motion with respect to the incident wave. The scattering power of the vortex ring is compared with that of a solid sphere of the same size. In the present analysis, no restriction is imposed about the magnitude of the incident wavelength so far as the scattered wave is a small perturbation to the incident one.

Kameyama, S., Yanagisawa, T., Ando, T., Sakimura, T., Tanaka, H., Furuta, M. and Hirano, Y.

"DEVELOPMENT OF WIND SENSING COHERENT DOPPLER LIDAR AT MITSUBISHI ELECTRIC CORPORATION FROM LATE 1990S TO 2013"

17th Coherent Lidar Conference, June 2013, Barcelona, Spain.

Since late 1990s, we have been developing the wind sensing coherent Doppler LIDARs. In the history of wind lidar, we have offered the following world-first topics, (1) wind sensing using eye-safe (1.5 micron) wavelength region, (2) instrumentation of compact fiber-based lidar, (3) product release of the fiber-based pulsed lidar, (4) middle-range (8 km) wind sensing with the high power fiber amplifier, (5) long-range (10 km) and real-time wind sensing using eye-safe wavelength, and (6) ultra-long-range (more than 30 km) wind sensing. Here, we introduce these topics and shortly describe about our future perspectives.

Kandil, O. A.

"PREDICTION AND CONTROL OF VORTEX DOMINATED AND VORTEX-WAKE FLOWS"

NASA-CR-202815, February 1996, Old Dominion Univ., Norfolk, VA

This report describes the activities and accomplishments under this research grant, including a list of publications and dissertations, produced in the field of prediction and control of vortex dominated and vortex wake flows.

Kandil, O. A. and Adam, I. G.

"EFFECTS OF EXHAUST PLUME TEMPERATURE ON VORTEX-WAKE/GROUND INTERACTION"

AIAA Paper No. 1998-2525, Albuquerque, NM, June 1998

The effect of exhaust plume temperature on the vortex-wake decent, separation and rebound near the ground is investigated. The three-dimensional, compressible Navier-Stokes (NS) equations are solved numerically. The implicit, upwind, Roe flux-differencing, finite volume scheme is used. The computations of vortex-wake/exhaust plume interaction with the ground are carried out using overlapping zonal method for long distances downstream. Typical velocity profiles of a tip vortex for Boeing 757 and Boeing 747, with and without exhaust plume temperature profiles, are used for inflow boundary conditions. The vortex-wake is subjected to crosswind flow and both upwind and downwind vortices are considered. The results of the vortex-wake decent, separation and rebound with and without exhaust plume are compared with each other.

Kandil, O. A. and Kandil, H. A.

"COMPUTATION OF COMPRESSIBLE QUASI-AXISYMMETRIC SLENDER VORTEX FLOW AND BREAKDOWN"

Computer Physics Communications, Vol. 65, 1991, pp. 164-172.

Analysis and computation of steady, compressible, quasi-axisymmetric flow of an isolated, slender vortex are considered. The compressible Navier-Stokes equations are reduced to a simpler set by using the slenderness and quasi-axisymmetric assumptions. The resulting set along with a compatibility equation are transformed from the diverging physical domain to a rectangular computational domain. Solving for a compatible set of initial profiles and specifying a compatible set of boundary conditions, the equations are solved using a type-differencing scheme. Vortex breakdown locations are detected by the failure of the scheme to converge. Computational examples include isolated vortex flows at different Mach numbers, external axial-pressure gradients, and swirl ratios. Excellent agreement is shown for a bench-mark case between the computed results using the slender vortex equations and those of a full Navier-Stokes solver.

Kandil, O. A., Adam, I. and Wong, T.-C.

"FAR-FIELD TURBULENT VORTEX-WAKE/EXHAUST PLUME INTERACTION FOR SUBSONIC AND HSCT AIRPLANES"

AIAA Paper No. 1996-1962, New Orleans, LA, June 1996

Computational study of the far-field turbulent vortex-wake/exhaust plume interaction for subsonic and high-speed civil transport (HSCT) airplanes is carried out. The Reynolds-averaged Navier-Stokes (NS) equations are solved using the implicit, upwind, Roe-flux-differencing, finite-volume scheme. The two-equation shear stress transport model of Menter is implemented with the NS solver for turbulent-flow calculation. For the far-field study, the computations of vortex-wake interaction with the exhaust plume of a single engine of a Boeing 727 wing in a holding condition and two engines of an HSCT in a

cruise condition are carried out using overlapping zonal method for several miles downstream. These results are obtained using the computer code FTNS3D. The results of the subsonic flow of this code are compared with those of a parabolized NS solver known as the UNIWAKE code.

Kandil, O. A., Chu, L.-C. and Yates Jr., E. C.

"HYBRID VORTEX METHOD FOR LIFTING SURFACES WITH FREE VORTEX FLOW"

AIAA Paper No. 1980-0070, January 1980, Pasadena, CA.

A Nonlinear Hybrid Vortex method (NHV-method) has been developed for predicting the aerodynamic characteristics of wings exhibiting leading- and side-edge separations. This method alleviates the drawbacks of the Nonlinear Discrete Vortex method, also known as the multiple line vortex method. The NHV-method combines continuous-vorticity and vortex-line representations of the wing and its separated free shear layers. Continuous vorticity is used in the near-field calculations, while discrete vortex-lines are used in the far-field calculations. The wing and its free shear layers are divided into quadrilateral vortex panels having second-order vorticity distributions. The aerodynamic boundary conditions and continuity of the vorticity distributions are satisfied at certain nodal points on the vortex panels. An iterative technique is used to satisfy these conditions to obtain the vorticity distribution and the wake shape. Distributions and total aerodynamic loads are then calculated.

Kandil, O. A., Kandil, H. A. and Liu, C. H.

"COMPUTATION OF STEADY AND UNSTEADY COMPRESSIBLE QUASI-AXISYMMETRIC VORTEX FLOW AND BREAKDOWN"

AIAA Paper No. 1991-0752, January 1991, Reno, NV.

The unsteady, compressible Navier-Stokes equations are used to compute and analyze compressible quasi-axisymmetric isolated vortices. The Navier-Stokes equations are solved using an implicit, upwind, flux-difference splitting finite-volume scheme. The developed three-dimensional solver has been verified by comparing its solution profiles with those of a slender, quasi-axisymmetric vortex solver for a subsonic, isolated quasi-axisymmetric vortex in an unbounded domain. The Navier-Stokes solver is then used to solve for a supersonic quasi-axisymmetric vortex flow in a configured circular duct. Steady and unsteady vortex-shock interactions and breakdown have been captured. The problem has also been calculated using the Euler solver of the same code and the results are compared with those of the Navier-Stokes solver. The effect of the initial swirl has been tentatively studied.

Kandil, O. A., Kandil, H. A. and Liu, C. H.

"SUPERSONIC QUASI-AXISYMMETRIC VORTEX BREAKDOWN"

AIAA Paper No. 1991-3311, September 1991, Baltimore, MD.

An extensive computational study of supersonic quasi-axisymmetric vortex breakdown in a configured circular duct is presented. The unsteady, compressible, full Navier-Stokes (NS) equations are used for the present computational study. The NS equations are solved for quasi-axisymmetric flows using an implicit, upwind, flux-difference splitting, finite-volume scheme. The quasi-axisymmetric solutions are time accurate and are obtained by forcing the components of the flow field vector to be equal on two axial planes, which are near each other. The computational study addresses the effect of the Reynolds number, for laminar flows, on the evolution and persistence of vortex breakdown. The effect of boundary conditions at the duct exit on vortex breakdown is also studied. Finally, the effect of swirl ratio at the duct inlet is investigated.

Kandil, O. A., Kandil, H. A. and Liu, C. H.

"CRITICAL EFFECTS OF DOWNSTREAM BOUNDARY CONDITIONS ON VORTEX BREAKDOWN"

AIAA Paper No. 1992-2601, June 1992, Palo Alto, CA.

The unsteady, compressible, full Navier-Stokes equations are used to study the critical effects of the downstream boundary conditions on the supersonic vortex breakdown. The present study is applied to two supersonic vortex breakdown cases. In the first case, quasi-axisymmetric supersonic swirling flow is considered in a configured circular duct, and in the second case, quasi-axisymmetric supersonic swirling jet, that is issued from a nozzle into a supersonic jet of lower Mach number, is considered. For the configured duct flow, four different types of downstream boundary conditions are used, and for the swirling jet flow from the nozzle, two types of downstream boundary conditions are used. The solutions are time accurate which are obtained using an implicit, upwind, flux-difference splitting, finite-volume scheme.

Kandil, O. A., Kandil, H. A. and Liu, C. H.

"THREE-DIMENSIONAL SUPERSONIC VORTEX BREAKDOWN"

AIAA Paper No. 1993-0526, January 1993, Reno, NV.

Three-dimensional, supersonic vortex-breakdown problems in bound and unbound domains are solved. The solutions are obtained using the time-accurate integration of the unsteady, compressible, full Navier-Stokes equations. The computational scheme is an implicit, upwind, flux-difference splitting, finite-volume scheme. Two vortex-breakdown applications are considered in the present paper. The first is for a supersonic swirling jet which is issued from a nozzle into a supersonic uniform flow at a lower Mach number than that of the swirling jet. The second is for a supersonic swirling flow in a configured circular duct. In the first application, an extensive study of the effects of grid fineness, shape and grid-point distribution on the vortex breakdown is presented. Four grids are used in this study and they show a substantial dependence of the breakdown bubble and shock wave on the grid used. In the second application, the bubble-type and helix-type vortex breakdown have been captured.

Kandil, O. A., Liu, C. H. and Sheta, E. F.

"EFFECTS OF COUPLED AND UNCOUPLED BENDING TORSION MODES ON TWIN-TAIL BUFFET RESPONSE"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

In this paper, the interactions of unsteady vortex-breakdown flow of a 76-degree sharp-edged delta wing with the vertical twin-tail configuration of Washburn et. al. is computationally produced and investigated. The formulation of the problem consists of three sets of governing equations along with certain initial and boundary conditions. The first set is the unsteady, compressible, Reynolds-averaged Navier-Stokes equations. The second set consists of the aeroelastic equations for coupled or uncoupled bending and torsional responses of the twin tail. The third set consists of equations for deforming the grid due to the deflections of the twin tail in bending and torsion. These sets are sequentially solved accurately in time at each time step.

Kandil, O. A., Wong, T.-C. and Liu, C. H.

"ANALYSIS AND COMPUTATION OF TRAILING VORTICES AND THEIR HAZARDOUS EFFECTS"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 36-1 - 36-24

The thin-layer, Reynolds-averaged, Navier-Stokes equations along with an implicit, upwind, flux-difference splitting, finite-volume scheme are used to compute the vortex wake of a large-aspect-ratio wing. A C-O grid with grid stretching at the wing leading, trailing and side edges is used to solve for the wing and its near-vortex wake flows. The computed surface-pressure distribution is validated by comparison with a set of experimental data. Next, a relatively small trailing wing, in comparison with the leading wing, having a large aspect ratio is introduced in the near-vortex wake of the leading wing. The trailing wing grid has also been stretched at critical interference locations. The interacting-wing problem is recomputed using the solution of the previous isolated-wing problem as the initial condition. Fixing the downstream separation distance, the spanwise location of the trailing wing is varied to simulate two flow interference problems. The first problem is called the 'along-track penetration through vortex center' and the second is called the 'along-track penetration between vortices'.

Kandil, O. A., Wong, T.-C. and Liu, C. H.

"TURBULENT FLOW OVER A 747/747 GENERATOR/FOLLOWER CONFIGURATION AND ITS DYNAMIC RESPONSE"

AIAA Paper No. 1994-2383, Colorado Springs, CO, June 1994

The multidisciplinary interaction of the aerodynamics and rigid-body dynamics between a single tip vortex (representing a 747-generator wing) and a trailing wing (representing a 747-follower wing) is computationally investigated. The three-dimensional computational model consists of a tip vortex with

prescribed location and flow profiles in the inlet boundary of the computational domain, and a 747-follower wing with prescribed location relative to the generator tip vortex and prescribed mass-moment of inertia around the wing axis of symmetry. Keeping the follower wing stationary, the problem is solved for the flow field using the Reynolds-averaged, Navier-Stokes (NS) equations. With this solution serving as initial conditions, the follower wing is released to roll under the effect of the rolling moment induced by the generator tip vortex. At each time step, the NS equations and the dynamics equation for rolling motion are solved sequentially for the flow field, the rolling moment and the follower wing rolling motion.

Kandil, O. A., Wong, T.-C., Adam, I. and Liu, C. H.

"PREDICTION OF NEAR- AND FAR-FIELD VORTEX-WAKE TURBULENT FLOWS"

AIAA Paper 1995-3470-CP, Baltimore, MD, August 1995

Prediction of both the near- and far-field vortex-wake turbulent flows are presented. The Reynolds-averaged Navier-Stokes (NS) equations are solved using the implicit, upwind Roe-flux-differencing scheme. The turbulence models of Baldwin and Lomax, one-equation model of Spalart and Allmaras and two-equation shear stress transport model of Menter are implemented with the NS solver for turbulent-flow calculation. For the near-field study, computations are carried out on a fine grid for a rectangular wing with a NACA-0012 airfoil section and a rounded tip. The wing has an aspect ratio of 1.5 and is mounted inside a wind tunnel at an angle of attack of 10 degrees. The focus of study is the tip-vortex development, the near vortex wake roll-up, and validating the results with the available experimental data. For the far-field study, the computations of vortex-wake interaction with the exhaust plume of a single engine are carried out using overlapping zonal method for a long distance downstream of a Boeing 727 wing in a holding condition. The results are compared with those of an incompressible parabolized NS solver known as the UNIWAKE code.

Kaniewski, M., Hahne, H. W. and Mitra, N. K.

"MASS TRANSFER ENHANCEMENT BY LONGITUDINAL VORTICES"

Heat and Mass Transfer, Vol. 32, 1997, pp. 163-166.

From numerical and experimental investigations, it has been recently established that convective heat transfer can be dramatically enhanced by the generation of longitudinal vortices in the flow. The phenomenological similarity between heat and mass transfer suggests that longitudinal vortices should increase also mass transfer. The mixing between two parallel streams of two components in a rectangular channel with and without a pair of rectangular winglets as vortex generators has been numerically investigated. The results show that one pair of vortex generators can increase the global mixing by more than 50 for laminar flow. This global mixing has been defined as the sum of the square of the differences of concentrations.

Kanki, B. G.

"DYNAMIC SPACING HUMAN FACTORS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 500-508

The dynamic spacing human factors project is part of the Aircraft-ATC System integration element of the NASA Terminal Area Productivity program. The goal of the research is to investigate human factors issues related to the effect of Aircraft Vortex Spacing System (AVOSS) technologies on air traffic controllers. AVOSS technologies are presumed to make it possible to reduce separation standards in the terminal area under specified meteorological conditions. To take advantage of reduced spacing, controllers will be required to shift from one set of standards to another depending on dynamically changing conditions. Human factors issues include controller limitations to incorporating dynamic changes (e.g., adequate transition time, acceptable workload), the identification of controller strategies for accommodating shifting standards, and consistency with current practices, training, policies, and regulations. In addition, it is critical to address the way the AVOSS technologies will interface with the Air Traffic Management system. The research incorporates an integrated approach utilizing both simulation and field research methods. A preliminary simulation study produced the following results: Controllers were able to achieve reduced separation during training but not during test runs when the separations shifted in the standard-to-reduced matrix direction. However, there was a great amount of controller performance variability which could be attributed to differences in skill, strategies and/or length of run effects.

Kantha, H. L., Lewellen, W. S. and Durgin, F. W.

"QUALITATIVE RESPONSES OF A VORTEX CORE TO TIP BLOWING AND INTERSECTING AIRFOILS"

ASRL TR 153-4, August 1971, MIT Aeroelastic and Structures Research Laboratory, Cambridge, MA.

This investigation deals with the qualitative responses of a trailing vortex core to changes in its convective velocity produced in two different ways, (a) by injection of air into the vortex core and (b) by the flow field of a lifting surface in the path of the core. Flow pictures of the vortex core and vorticity measurements in the core show that an axial momentum injection of approximately 35 percent of the total wing drag alters the vortex structure and behavior quite drastically by effectively inducing a more rapid dispersion of the vorticity in the core. The data indicates that the phenomenon is governed by the rate of injection of the momentum rather than the mass flow rate as reported recently by Reinhart. There also seems to be an optimum rate of injection beyond which increased injection does not bring about equally significant changes in the vortex core. Flow patterns of the region of interaction between the flow field of a lifting surface and the vortex core show two modes of vortex response: (a) the vortex core bends, following the streamline shape until it intercepts the wake of the wing where it is abruptly dispersed, or (b) the vortex core may be sliced into two smaller vortices when the vortex hits the leading edge of the wing.

Kantha, H. L., Lewellen, W. S., and Durgin, F. H.

"RESPONSE OF A TRAILING VORTEX TO AXIAL INJECTION INTO THE CORE"

Journal of Aircraft, Vol. 9, No. 3, March 1972, pp. 254-256

The present investigation demonstrates that axial injection into the core of a vortex can indeed beneficially spread out the vorticity concentrated in it and prematurely age it. It further shows that the phenomenon is more nearly governed by the momentum flux of injection than by mass flow. A suitable value of injection for which substantial changes are produced in the vortex core appears to correspond to roughly 0.35. Despite the relatively high value of injection needed, this provides a possibly feasible way to disperse trailing vortices, since all of the injection required may be obtained by a redistribution of thrust.

Kantha, L.

"DECAY OF AIRCRAFT WAKE VORTICES UNDER DAYTIME FREE CONVECTIVE CONDITIONS"

Journal of Aircraft, Vol. 47, No. 6, Nov.-Dec. 2010, pp. 2159-2164.

The study suggests that separation times can be prudently lowered based on actual measured values of the turbulence kinetic energy dissipation rate. Doppler lidars may therefore play a critical role in enhancing the handling capacity of busy airports around the world, since they provide the capability to remotely measure the turbulence kinetic energy dissipation rate all along the flight corridor. Strong daytime convective conditions are often associated with good visibility; hence, visual flight rules prevail, and separation distances are reduced upon request by the pilots. However, the separation distances (times) could also be reduced under poor visibility and instrument flight rules, in particular, category 1 conditions.

Kantha, L. H.

"EMPIRICAL MODEL OF TRANSPORT AND DECAY OF WAKE VORTICES BETWEEN PARALLEL RUNWAYS"

Journal of Aircraft, Vol. 33, No. 4, July-August 1996, pp. 752-760

This article describes a simple empirical model for the transport and decay of aircraft trailing wake vortices between parallel runways in a turbulent atmosphere. It is suitable for applications to both single and closely spaced parallel runways. The model includes the influence of ambient turbulence on the decay rate of the wake vortices as well as the effect of crosswind shear. Well-known Monin-Obukhov similarity laws in the lower atmospheric boundary layer are used to compute the ambient shear and turbulence. Vortex bounce that occurs near the ground is also parameterized in the model. The results show that ambient shear plays an important role in vortex decay and transport. Atmospheric stability also affects the fate of these vortices, but with stable stratification having a much larger effect than convective heating of the atmospheric boundary layer. These results may prove useful for a better understanding of the factors that affect the transport and decay of aircraft wake vortices near the ground in the presence of crosswinds in a turbulent atmosphere.

Kantha, L. H.

"EMPIRICAL MODEL OF TRANSPORT AND DECAY OF AIRCRAFT WAKE VORTICES"

Journal of Aircraft, Vol. 35, No. 4, July-August 1998, pp. 649-653

An earlier empirical model of the transport and decay of aircraft wake vortices has been extended to include the effect of the decrease in the vortex circulation caused by ambient turbulence and shear, the shear-induced tilt of the vortex oval, and the initial roll-up phase. In addition to simulating the vortex bounce frequently observed near the ground, the model is now formulated to simulate the accelerated decay of the downwind vortex in crosswind shear, which often leads to the phenomenon of a lone surviving vortex. The ambient crosswind shear produces a vortex pair tilt with the downwind vortex being higher at normal crosswind speeds. Quite high crosswinds are needed to tilt the vortex in the other direction, where the upwind vortex is higher.

Kao, D. L.

"AUTOMATED VORTEX CORE ANALYSIS FOR MULTI-ZONE NUMERICAL FLOW SIMULATIONS"

AIAA Paper No. 2011-3679, June 2011, Honolulu, Hawaii.

An automated approach is implemented to perform data analysis of vortex cores extracted from numerical flow simulations. The new approach generates contiguous vortex core lines in multi-zone grids. Then, several interactive techniques are presented that extract quantitative data such as cross-flow velocity profiles and vortex core diameter. The approach provides a faster way of analyzing flow features than is possible using conventional post-processing tools. Furthermore, it provides a new way of analyzing vortex cores.

Kao, D. L. and Chaderjian, N. M.

"AUTOMATIC TIP VORTEX CORE PROFILING FOR NUMERICAL FLOW SIMULATIONS OF ROTORCRAFT IN HOVER"

AIAA Paper No. 2010-4752, June 2010, Chicago, IL.

An automated approach is presented that extracts visual and quantitative data from vortex cores produced by Navier-Stokes simulations of rotorcraft in hover mode. This approach extracts contiguous rotor tip vortex-core trajectories, cross-flow velocity profiles, and vortex-core diameter variation with wake age (azimuthal angle). This automated approach is faster and more accurate than a conventional manual approach. Moreover, this new approach allows for an efficient way to quantitatively compare vortex-core profiles from different flow simulations, e.g., grid resolution studies, and validate computed results with experimental data.

Kao, D. L., Ahmad, J. U., Holst, T. L. and Allan, B. G.

"VISUALIZATION AND ANALYSIS OF VORTEX FEATURES IN HELICOPTER ROTOR WAKES"

AIAA Paper 2013-1162, January 2013, Grapevine, TX.

Vortex interactions in helicopter rotor wakes are visualized using enhanced flow visualization techniques, which in turn play a crucial role in understanding the dynamics of these complex flows. Iso-surfaces are clipped in a 3D volume to reduce visual clutter. Flow textures are improved to highlight vortical flow structure and vortex-wake interactions. These visualization techniques are applied to three Computational Fluid Dynamics (CFD) simulations of helicopter flow fields. The presented techniques provide a good depiction of rotor tip vortices in these flows.

Kao, D. L., Smith, K. L. and Liu, Z.

"TRACKING BLADE TIP VORTICES FOR NUMERICAL FLOW SIMULATIONS OF HOVERING ROTORCRAFT"

AIAA Paper 2018-1175, January 2018, Kissimmee, FL.

Blade tip vortices generated by a helicopter rotor blade are a major source of rotor noise and airframe vibration. The noise and vibration occur when a vortex passes close to, and interacts with, a rotor blade. Accurate prediction of Blade Vortex Interaction (BVI) remains a challenge for Computational Fluid Dynamics (CFD). Although considerable research has been devoted to BVI noise reduction and experimental techniques for measuring the blade tip vortices in a wind tunnel, there are only a handful of post-processing tools available for extracting vortex core lines from CFD simulation data. To obtain the vortex core radius, most of these tools require the user to manually select a vortex core to perform the calculation. Furthermore, none of these tools provide an ability to track the growth of a vortex core, which is a measure of how quickly the vortex diffuses over time. This paper introduces an automated approach for tracking the core growth of a blade tip vortex from CFD simulations of rotorcraft in hover. The proposed method enables effective quantification and visualization of blade tip vortices in helicopter rotor wakes.

Kao, H. C.

"BODY-VORTEX INTERACTION, SOUND GENERATION AND DESTRUCTIVE INTERFERENCE"

NASA TM-2000-210239, August 2000, NASA Glenn Research Center at Lewis Field, Cleveland, OH.

It is generally recognized that the interaction of vortices with downstream blades is a major source of noise production. To analyze this problem numerically, a two-dimensional model of inviscid flow together with the method of matched asymptotic expansions is proposed. The method of matched asymptotic expansions is used to match the inner region of incompressible flow to the outer region of compressible flow. Because of incompressibility, relatively simple numerical methods are available to treat multiple vortices and multiple bodies of arbitrary shape. Disturbances from vortices and bodies propagate outward as sound waves. Due to their interactions, either constructive or destructive interference may result. When it is destructive, the combined sound intensity can be reduced,

sometimes substantially. In addition, an analytical solution to sound generation by the cascade-vortex interaction is given.

Kao, H. C.

"BODY-VORTEX INTERACTION, SOUND GENERATION, AND DESTRUCTIVE INTERFERENCE"

AIAA Journal, Vol. 40, No. 4, April 2002, pp. 652-660.

It is generally recognized that the interaction of vortices with downstream blades is a major source of noise production. To analyze this problem numerically, a two-dimensional model of inviscid flow, together with the method of matched asymptotic expansions, is proposed. The method of matched asymptotic expansions is used to match the inner region of incompressible flow to the outer region of compressible flow. Because of incompressibility, relatively simple numerical methods are available to treat multiple vortices and multiple bodies of arbitrary shape. Disturbances from these vortices and bodies propagate outward as sound waves. Because of their interactions, either constructive or destructive interference may result. When it is destructive, the combined sound intensity can be reduced, sometimes substantially.

Kapernick, K., Koop, L., Ehrenfried, K. and Dillmann, A.

"DYNAMICS OF FLAP SIDE-EDGE VORTICES"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

One dominant source of airframe noise is situated at the side edge of an extended wing flap. Oscillation of the vortical structure at the flap side-edge has been proposed by various authors as one possible mechanism of sound generation. The objective of the present study is to reduce this noise by blowing air into the vortical structure. The basic idea behind this concept is to displace or destroy the vortical structure, reducing the surface pressure level and thus the amplitude of the radiated sound. To investigate the technical feasibility, particle image velocimetry (PIV) and sound pressure level measurements are performed on a swept constant chord half model. The PIV measurements yield a rather complicated and unsteady vortical structure which confirms the assumption of a noise source at the flap side-edge. The vortical structure can be almost completely dispersed by blowing, thus resulting in a significant reduction of the sound pressure level.

Kaplan, M. L.

"MULTI-SCALE OBSERVATIONAL AND NUMERICAL MODELING STUDIES OF THE TURBULENCE ENVIRONMENT"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 15, 2016, Springer International Publishing Switzerland, pp. 299-316.

In this chapter, the focus will be on diagnosing multi-scale dynamical and thermodynamical processes that produce a favorable environment for aviation turbulence. In particular, the chapter will describe possible links among circulations at multiple scales of atmospheric motion that likely are favorable for the downscale generation of severe aviation turbulence. The chapter will be composed of three sections: (1) a synoptic/meso-alpha scale observational analysis of a broad cross section of turbulence accidents and the larger scale flow patterns that likely create a favorable mesoscale environment for the development of the turbulence event, (2) numerical simulations of the downscale dynamic/thermodynamic focusing of a favorable turbulence environment including the intersection of features at the synoptic, meso-alpha ($L = 200\text{-}2000\text{ km}$), and meso-beta ($L = 20\text{-}200\text{ km}$) scales of motion, and (3) an example of an operational mesoscale numerical model-based turbulence forecasting system and its implications for how it can be employed to determine the processes resulting in an environment which organizes severe aviation turbulence. These three sections are based upon research in Kaplan et al. (Characterizing the severe turbulence environments associated with commercial aviation accidents, 2004; Meteorol. Atmos. Phys. 88:129-152, 2005a; Meteorol. Atmos. Phys. 88:153-175, 2005b; Meteorol. Atmos. Phys. 94:235-270, 2006). We conclude with a summary and synthesis of a multi-scale paradigm for the downscale organization of a favorable aviation turbulence environment.

Kaplan, M. L., Lin, Y.-L., Charney, J. J., Pfeiffer, K. D., Ensley, D. B., DeCroix, D. S. and Weglarz, R. P.

"A TERMINAL AREA PBL PREDICTION SYSTEM AT DALLAS-FORT WORTH AND ITS APPLICATION IN SIMULATING DIURNAL PBL JETS"

Bull. Amer. Met. Society, Vol. 81, No. 9, September 2000, pp. 2179-2204

A state-of-the-science meso-beta-scale numerical weather prediction model is being employed in a prototype forecast system for potential operational use at the Dallas-Fort Worth International Airport (DFW). The numerical model is part of a unique operational forecasting system being developed to support the National Aeronautics and Space Administration's (NASA) Terminal Area Productivity Program. This operational forecasting system will focus on meso-beta-scale aviation weather problems involving planetary boundary layer (PBL) turbulence, and is named the Terminal Area PBL Prediction System (TAPPS). TAPPS (version 1) is being tested and developed for NASA to improve 1-6 h terminal area forecasts of wind, vertical wind shear, temperature, and turbulence within both stable and convective PBLs at major airport terminal areas. This is being done to enhance terminal area productivity, that is, aircraft arrival and departure throughput, by using the weather forecasts as part of the Aircraft Vortex Spacing System (AVOSS). AVOSS is dependent upon nowcasts or short-period forecasts of wind, temperature, and eddy dissipation rate so that the drift and dissipation of wake vortices can be anticipated for safe airport operation. This paper describes the numerical modeling system, which has three basic components: the numerical model, the initial data stream, and the postprocessing system.

Kaplan, M. L., Lin, Y.-L., Ringley, C. J., Brown, Z. G., Kiefer, M. T., Suffern, P. S. and Hoggarth, A. M.

"WAKE VORTEX ENVIRONMENT SIMULATIONS FROM A TERMINAL AREA PBL PREDICTION SYSTEM (TAPPS)"

AIAA Paper No. 2006-1074, Reno, NV, January 2006.

This paper describes the development of a system to predict wake vortex environmental climatologies at major airports. This research model represents the precursor to a modeling system that ultimately could be run in real time to predict the atmospheric environment that controls wake vortex translation and dissipation. In this paper we will describe the most recent efforts to validate the numerical modeling system against field experiment observations compiled by NASA during the Aircraft Vortex Observation and Spacing System (AVOSS) field experiment held at Dallas-Fort Worth International Airport (DFW) on 15-19 September 1997. The paper will first describe the numerical modeling system followed by the results of the validation of simulations against available rawinsonde and boundary layer observations surrounding and at DFW.

Kaplan, M. L., Weglarz, R. P., Lin, Y.-L., Ensley, D. B., Kehoe, J. K. and Decroix, D. S.

"A TERMINAL AREA PBL PREDICTION SYSTEM FOR DFW"

AIAA Paper No. 1999-0983, Reno, NV, January 1999

A state-of-the-science mesoscale numerical weather prediction model is being tested in a prototype mode for potential operational use in support of NASA's Terminal Area Productivity (TAP) Program at the Dallas-Fort Worth (DFW) International Airport. The numerical model is the key component of a mesoscale weather prediction system named the Terminal Area PBL Prediction System (TAPPS). TAPPS is being developed and tested for NASA to improve short period forecasts of wind, wind shear, temperature, and turbulence within stable and convective planetary boundary layers (PBL). This is being done to enhance terminal area productivity by using the weather forecasts as part of the Aircraft Vortex Spacing System (AVOSS). In this paper we describe the real time numerical modeling system which has three basic components: (i) the numerical model, (ii) the initial data stream, and (iii) the postprocessing system. We also compare the results of several case study simulations with data collected from a field program held during September 1997 at DFW. During this field program, detailed local measurements of the PBL as well as the entire troposphere were taken in an effort to verify the numerical model results. Comparisons indicate that the numerical model is capable of accurately simulating the vertical wind shear structure during the diurnal evolution of the planetary boundary layer. Special emphasis in comparisons between the numerical model and observations are placed on the dynamics of the Great Plains nocturnal low-level jet, which represents the dominant low-level wind shear-production mechanism during many synoptic scale weather regimes.

Kaplan, M. L., Weglarz, R. P., Lin, Y.-L., Langmaid, A. H. and Hamilton, D. W.

"THE APPLICATION OF MESOSCALE NUMERICAL WEATHER PREDICTION MODELS TO THE TERMINAL AREA AND EXAMPLES FROM MEMPHIS 1995 FIELD DATA"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 430-459

This presentation will focus on the new weather forecast system which is designed to support AVOSS, i.e., the Terminal Area Planetary boundary layer Prediction System (TAPPS). The system will be described in terms of its two primary components which represent state-of-the-science mesoscale numerical weather prediction models. The first component is the Mesoscale Atmospheric Simulation System (MASS). This numerical model is designed to simulate phenomena which have spatial scales > 100 km and temporal scales of 3 hours or greater. It is initialized from synoptic scale data including radiosonde, wind profiler, satellite, radar, and surface observations. MASS will then act to provide the initial and lateral boundary conditions for a cloud/LES scale numerical model known as the Terminal Area Simulation System (TASS). TASS then enables the forecast system to be applied to the county scale/aviation terminal area for time periods of < 3 hours with a specific focus on predicting localized planetary boundary layer phenomena. One of the most important aspects of short period local terminal weather is the problem of rapidly developing low-level jet streams. These wind maxima can have a dramatic effect upon the transport and dynamics of wake vortices just above the earth's surface.

Kaplan, S. M., Altman, A. and Ol, M.

"WAKE VORTICITY MEASUREMENTS FOR LOW ASPECT RATIO WINGS AT LOW REYNOLDS NUMBER"

Journal of Aircraft, Vol. 44, No. 1, January-February 2007, pp. 241-251

Trailing vortex structure of low aspect ratio wings was studied in a water tunnel at Reynolds numbers of 8000 and 24,000 using dye injection and digital particle image velocimetry in cross-flow planes in the near wake, for rectangular, semi-elliptical, and delta-wing planforms. The velocity data were used to calculate lift via circulation and effective span, and the results were compared with force balance measurements and classical inviscid theory. The objectives of the study were to assess how low-Reynolds number effects might affect the measurement of lift coefficient from tip-vortex circulation, how well the measurements fit the various theoretical models of lift curve slope for low aspect ratio wings, and the extent to which planform shape affects lift coefficient while aspect ratio and planform area are kept constant. All models were thin flat plates with square edges. For the conditions studied, apparent viscous effects on vorticity integrations in the wake were small, resulting in good agreement between lift coefficient values inferred from the measurements, the force balance data, and the classical inviscid formulas. Whereas the three wings exhibited distinctly different wake structures, lift curve slopes were similar.

Kaplan, S. M., Altman, A. and Ol, M.

"ANGLE OF ATTACK AND PLANFORM EFFECTS ON FLAT PLATE TRAILING VORTICES AT LOW REYNOLDS NUMBERS"

AIAA Paper No. 2006-246, Reno, NV, January 2006

Tip vortices of low aspect ratio wings were studied in a water tunnel at Reynolds numbers of 8000 and 24,000, with dye injection and digital particle image velocimetry in crossflow planes in the near wake, for rectangular, semi-elliptical and delta-wing planforms. The velocity data were used to calculate lift via circulation, and the results were compared with direct force measurements. The objectives of the study were to assess how low Reynolds number effects might affect the classical measurement of lift coefficient from tip-vortex circulation, how well the measurements fit the slender wing theory lift curve slope, and the extent to which planform shape affects lift coefficient while aspect ratio and area are kept constant. All models were thin flat plates with square edges. For the range of streamwise locations and angles of attack studied, apparent viscous effects on vorticity in the wake were small, resulting in good agreement between lift coefficient values inferred from the measurements, the force balance data, and the classical inviscid formulas.

Kaplanski, F. B. and Rudi, Y. A.

"A MODEL FOR THE FORMATION OF 'OPTIMAL' VORTEX RINGS TAKING INTO ACCOUNT VISCOSITY"

Physics of Fluids, Vol. 17, August 2005, pp. 087101-1-087101-.

The evolution of a viscous vortex ring from thin to thick-cored form is considered using an improved asymptotic solution, which is obtained after impressing a spatially uniform drift on the first-order solution of the Navier-Stokes equations. The obtained class of rings can be considered as the viscous analog solution to the Norbury vortices and classified in terms of the ratio of their initial outer radius to the core radius. The model agrees with the reported theoretical and experimental results referring to the post-formation and the formation stages. By using the matching procedure suggested earlier and the obtained properties of the viscous vortex ring, it is found that when the length-to-diameter aspect ratio L/D reaches the limiting value 4.0 ('formation number'), the appropriate values of the normalized energy and circulation become around 0.3 and 2.0, respectively. An approach that enables to predict the 'formation number' is proposed.

Kaplanski, F., Fukumoto, Y. and Rudi, Y.

"REYNOLDS-NUMBER EFFECT ON VORTEX RING EVOLUTION IN A VISCOUS FLUID"

Physics of Fluids, Vol. 24, 2012, pp. 033101-1 - 033101-13.

It is known that the cross section of the vortex ring core takes an approximately elliptical shape with increasing Reynolds number. In order to model this feature, the functional form of a vortex ring solution of the Stokes equations is modified to be able to model higher Reynolds number rings. The model introduces two nondimensional parameters that govern the shape of the vortex core: d greater than or equal to 1 and b greater than or equal to 1. Based on this modification, new expressions for the translation velocity, energy, circulation, and stream function are derived for a wide range of section ellipticity that are specific to such vortices. To validate the model, the data adapted from the numerical study of vortex ring at Reynolds number 1400 performed by Danaila and Helie is used. In this case, the appropriate values of d and b are calculated by equating the normalized energy and circulation of the

theoretical vortex to the corresponding values obtained from the numerical data. The model provides a good prediction of the ring velocity evolution at high Reynolds numbers.

Kaplanski, F., Sazhin, S. S., Fukumoto, Y., Begg, S. and Heikal, M.

"A GENERALIZED VORTEX RING MODEL"

Journal of Fluid Mechanics, Vol. 622, 2009, pp. 233-258.

A conventional laminar vortex ring model is generalized by assuming that the time dependence of the vortex ring thickness L is given by the relation $L = a \text{ times } t \text{ to the } b \text{ power}$, where a is a positive number and b is greater than or equal to $1/4$ and less than or equal to $1/2$. In the case in which $a = \text{the square root of } 2\nu$, where ν is the laminar kinematic viscosity, and $b = 1/2$, the predictions of the generalized model are identical with the predictions of the conventional laminar model. In the case of $b = 1/4$ some of its predictions are similar to the turbulent vortex ring models, assuming that the time-dependent effective turbulent viscosity is equal to $L \text{ times } L \text{ prime}$. This generalization is performed both in the case of a fixed vortex ring radius R and increasing vortex ring radius. In the latter case, the so-called second Saffman's formula is modified. In the case of fixed R , the predicted vorticity distribution for short times shows a close agreement with a Gaussian form for all b and compares favorably with available experimental data. The time evolution of the location of the region of maximal vorticity and the region in which the velocity of the fluid in the frame of reference moving with the vortex ring centroid is equal to zero is analyzed. It is noted that the locations of both regions depend upon b , the latter region being always further away from the vortex axis than the first one. It is shown that the axial velocities of the fluid in the first region are always greater than the axial velocities in the second region.

Kaplanskii, F. B. and Rudi, Y. A.

"EVOLUTION OF A VISCOUS VORTEX RING"

Fluid Dynamics, Vol. 36, No. 1, 2001, pp. 16-25

The velocity field inside a viscous vortex ring and its overall velocity are obtained based on an existing solution of the Stokes equation for the vorticity in a moving coordinate system. It is shown that these characteristics of the motion relate the results obtained earlier for limiting times and are confirmed by the experimental data. The effect of the initial Reynolds number on the development of the vortex ring is analyzed by constructing entrainment diagrams.

Karakus, C., Akilli, H. and Sahin, R.

"FORMATION, STRUCTURE, AND DEVELOPMENT OF NEAR-FIELD WING TIP VORTICES"

Proc. IMechE, Vol. 222, Part G, 2008, pp. 13-22.

The current experimental study investigates the details of the formation, structure, and development of wing tip vortices that are generated by an airfoil of NACA0012 profile having a rectangular planform

of 151 mm chord using the particle image velocimetry technique. Experiments have been carried out at different angles of attack, which affect the vortex strength, vortex size, tangential velocity, and vorticity distribution along the downstream stations at chord lengths ranging from $x/c = 0.1$ to 1.6 , at a fixed free-stream velocity of 212 mm/s corresponding to the Reynolds number, $Re = 32000$ based on the chord length. The radius of the vortex core is found to vary approximately between 5 and 7.5 per cent of the chord length of the wing. The results show that the flow around the tip is dominated by the structures of multiple vortices. The maximum normalized tangential velocity increases with increasing angle of attack. The peak magnitude of the tangential velocity is about 15 per cent of the free-stream velocity for an angle of attack of 4° , whereas it is about 40 per cent of the free-stream velocity for 12° .

Karcher, B.

"AVIATION-PRODUCED AEROSOLS AND CONTRAILS"

Surveys in Geophysics, Vol. 20, 1999, pp. 113-167.

Liquid and solid particles in the plumes of jet aircraft cruising in the upper troposphere and lower stratosphere lead to the formation of ice clouds (contrails), modify the microphysical properties of existing cirrus clouds, and provide sites for heterogeneous chemical reactions. Characterization of aviation-produced particles in terms of physico-chemical properties is an important step in assessing the global impact of aircraft emissions upon atmospheric chemistry and climate parameters. Chemistry and microphysics of the gas-aerosol system in aircraft plumes and its evolution in the atmosphere is a field of intense research. This paper reviews the current knowledge (mid-1998) and outlines possible atmospheric implications.

Karkehabadi, R.

"AERODYNAMIC INTERFERENCE OF A LARGE AND A SMALL AIRCRAFT"

J. Aircraft, Vol. 41, No. 6, Nov.-Dec. 2004, pp. 1424-1429

The influence of wake from a leading aircraft, Boeing 757, on a following aircraft, Cessna 750 Citation X, is investigated using the unsteady vortex lattice method. The effect of the wakes from both wings and each other is considered and the new position of the wakes from both aircraft calculated. As the midspan of the Cessna wing approaches the Boeing 757 trailing vortex core, the roll moment increases to its maximum value. Strong changes appear in aerodynamic loads of the Cessna as it moves near the Boeing 757's wake. Rapid change occurs as the Cessna moves in transverse or vertical directions near the Boeing's wake. The unsteady aerodynamic loads on wings moving along different paths are calculated. The Boeing 757's wake strongly affects the aerodynamic loads and the wake of the Cessna. Also included in the present results are numerical simulations of wakes and velocity vectors in the Trefftz plane detailing the influence of the wake from the leading aircraft, the Boeing 757.

Karkehabadi, R.

"WIND TUNNEL MEASUREMENTS OF HAZARD POSED BY LIFT-GENERATED WAKES"

J. Aircraft, Vol. 32, No. 2, November-December 2004, pp. 1424-1429

The influence of wake from a leading aircraft, Boeing 757, on a following aircraft, Cessna 750 Citation X, is investigated using the unsteady vortex lattice method. The effect of the wakes from both wings and each other is considered and the new position of the wakes from both aircraft calculated. As the midspan of the Cessna wing approaches the Boeing 757 trailing vortex core, the roll moment increases to its maximum value. Strong changes appear in aerodynamic loads of the Cessna as it moves near the Boeing 757's wake. Rapid change occurs as the Cessna moves in transverse or vertical directions near the Boeing's wake. The unsteady aerodynamic loads on wings moving along different paths are calculated. The Boeing 757's wake strongly affects the aerodynamic loads and the wake of the Cessna. Also included in the present results are numerical simulations of wakes and velocity vectors in the Trefftz plane detailing the influence of the wake from the leading aircraft, the Boeing 757.

Karlsson, A. and Fuchs, L.

"TIME EVOLUTION OF THE VORTEX BETWEEN AN AIR INLET AND THE GROUND"

AIAA Paper No. 2000-0990, Reno, NV, January 2000

The flow near the inlet of a gas turbine engine intake located close to the ground is studied through Large Eddy Simulations (LES). The suction through the air inlet induces a vortex system, which is not only turbulent but also contains larger unsteady vortices. These vortices can be characterized through their geometrical shape and characteristic frequencies. The latter parameter discloses that there are several different modes of vortex systems. The transitions among the modes have been verified to be independent of the numerical parameters of the LES. We also notice that some of the vortices have a tendency of moving fluid from ground up into the air-intake. These vortices have a time dependent strength and 'origin' near the ground. The LES results have been compared qualitatively to experimental data reported in the literature. Our results indicate that LES can capture the details found in the experiments.

Karpatne, A.

"INVESTIGATION OF TIP VORTEX APERIODICITY IN THE WAKE OF A HELICOPTER IN HOVER"

MS Thesis, August 2012, University of Texas, Austin, Texas.

Previous research has indicated aperiodicity in the position of tip vortices emitted from a helicopter rotor blade in hover. The objective of the current study is to develop an analysis of the tip vortex aperiodicity in hover and to validate it with measurements on a reduced-scale, 1m diameter, four-bladed rotor. A 'vortex ring emitter model' (VREM) was developed to study the statistics of the tip vortices emitted from a rotor blade during hover. To better model the rotor wake, several independent vortex blobs were used to describe a vortex ring. An empirical model for viscosity was also considered

which helped model the core radius growth of the vortex ring with vortex age. A parametric analysis was then performed to obtain a comprehensive qualitative and quantitative convergence study of the time step, viscosity parameter, initial core size, number of rings shed, number of blobs and overlap factor. It was observed that the solution converged rapidly for all the parameters used. The locations of tip vortex cores for vortex ages ranging from 0 to 260 degrees were measured on the reduced-scale rotor using a stereo PIV system. The blade loading for the reduced scaled rotor was 0.044 and the blade rotational speed was 1520 RPM, which corresponds to a tip Reynolds number of 248,000. The 95 percent confidence region for the position of tip vortex cores exhibited an anisotropic, aperiodic pattern, approximating an ellipse. It was seen that the principal axis of this ellipse appeared to be aligned perpendicular to the slipstream boundary. The analytical model showed good correlation with experimental data in terms of the orientation and extent of the anisotropy. Moreover, an estimate of the total thrust produced and spanwise loading along the rotor blade was also obtained and compared with Blade Element Momentum Theory (BEMT). It was seen that by using more blobs to represent a vortex ring, the solution converged to the BEMT estimate..

Karpel, M., Shousterman, A., Reyes, M. and Climent, H.

"DYNAMIC RESPONSE TO WAKE ENCOUNTER"

AIAA Paper 2013-1921, April 2013, Boston, MA.

Wake vortices generated by an aircraft might cause severe structural dynamic response of an aircraft that encounters the wake while its strength is still high. Realistic wake-encounter cases might adversely affect the mission of the crossing aircraft or yield critical structural design loads cases. A numerical scheme for calculating the response of aeroelastic systems in such cases is presented. The new scheme is utilized in the Dynresp code for industrial dynamic loads calculations, taking advantage of its computational efficiency, feedback-loop capabilities and applicability with most general gust inputs, local aerodynamic outputs, and control-system architecture. The WESDE preprocessor that calculates the wake-induced incidence angles at the aerodynamic panels in arbitrary crossing parameters is also presented. The response formulation with new gust inputs is shown to be significantly different than that of standard gust-response schemes. Frequency-domain solutions and FFT schemes are combined for an efficient, robust and adequately accurate numerical process for massive industrial applications. Propeller-engine 1P load effects are included. Unsteady aerodynamic lag effects are shown to be especially important in fast wake encounter, and well represented by feedback filters that approximate Kussner's sharp-edge gust function by rational functions in the Laplace domain. Numerical examples with a generic transport aircraft and with the A400M military transport show well-behaved a-symmetric modal solutions. Very good comparisons are shown between numerical and A400M flight-test results.

Karwal, A. K.

"WAKE VORTEX FLIGHT TESTING IN RECENT EU RESEARCH PROGRAMS"

17th SFTE (EC) Symposium, June 2006, Amsterdam, The Netherlands

Predominantly driven by the need to increase airport capacity, but punctuated by the topical discussion on adequate separation criteria behind larger aircraft such as the An-225, A380 and the future B747-800, several European research programs have been launched aimed at expanding the knowledge of wake vortices and their effect on the overall safety level of the air transport system. These programs are designated by telltale acronyms such as M-FLAME, C-WAKE, WakeNet, S-WAKE, I-WAKE, ATC-WAKE, WAKEOP, AWIATOR, CREDOS and FAR-WAKE. In these programs different experimental techniques (such as the use of wind tunnel, water tank, ground lidar and catapult facilities, CFD computations, piloted simulations, and flight trials) are applied as tools to investigate vortex characteristics, to determine the effects of active or passive wake vortex control (alleviation) devices and to assess the impact on flight safety of a wake encounter. A few of these research programs (notably S-WAKE, I-WAKE, and AWIATOR) included actual flight tests to determine the correlation between the mentioned techniques with full-scale results and to get measurements that are difficult to obtain in a laboratory environment. NLR aircraft have participated in these programs, the paper will discuss practical issues related to aircraft instrumentation, test preparation and execution and some results of the flight test programs that were performed. Upcoming developments in the field of wake vortex flight testing are addressed as well.

Kashevarov, A. V., Potapov, Y. F. and Stasenko, A. L.

"NUMERICAL INVESTIGATION OF CHEMICALLY REACTING JETS OF AN AIRLINER AT LOW ALTITUDES"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 303-309

The work presents numerical investigation of the spatial-temporal evolution of chemically reacting components in an axisymmetric jet of an aircraft's engine, which are of interest both from a standpoint of airport ecology and as potential tracers for wake visualization by use of resonance sounding. Characteristic photochemical reactions were also taken into consideration. Computations were performed for a B-747-type aircraft flying at sea level.

Kashitani, M., Kita, Y., Suzuki, H., Yamaguchi, Y., Date, H. and Takita, Y.

"A FUNDAMENTAL STUDY ON AIRCRAFT MODEL BY WAKE MEASUREMENTS IN LOW-SPEED WIND TUNNELS"

AIAA Paper 2013-1022, January 2013, Grapevine, TX.

In this paper, the drag prediction method (wake integration method) based on the momentum conservation theorem was applied to the aerodynamic investigations on aircraft model. The wake survey of the model is performed to obtain the basic data to evaluate how applicable the technique is to aerodynamic tests in a relatively small low-speed wind tunnel. In this case, it is important to

investigate the effect of the measurement interval by the wake survey. The aircraft model is the same geometry model that was used for the correction wind tunnel test previously. The free-stream velocity is kept to be 30 m/s. The Reynolds number based on the mean aerodynamic chord length is $Re = 270,000$. The results are shown as follows. The section lift coefficient of 20 mm measurement interval shows the good agreement with the result of 5 mm interval. And as for the spanwise induced drag coefficient distribution, the distribution of 20 mm interval does not show quantitative agreement with the result of 5 mm interval. On the lift coefficient, the data of the wake measurement of 20 mm and 5 mm interval shows the good agreement with the results of the balance system. In the detail consideration, the result of 5 mm interval is 2.6 percent closer to the result by the balance system than the result of 20 mm interval. This difference of the present experimental data may be considered the effect of the flow unsteadiness and the measurement interval.

Kasim, K. A., Mat, S., Ishak, I. S. and Said, M.

"EFFECTS OF PROPELLER LOCATIONS ON THE VORTEX SYSTEM ABOVE DELTA-SHAPED UAV MODEL"

ICAS-2016-0162, September 2016, Daejeon, Korea.

The flow above delta wing is complicated and dominated by a very complex vortex structure. This study investigates the effects of propeller locations on the aerodynamic characteristics above a 55-degree sharp-edged non-slender delta wing UAV model. The experiments were conducted in a closed circuit UTM-LST wind tunnel at speeds of 20 and 25 m/s. In this project the propeller is located at three different locations namely; front, middle and rear. The result obtained from this experiment was compared with the clean wing configuration. The effects of propeller locations, angle of attack, Reynolds number and propeller advance ratio on the aerodynamic characteristics of this generic UAV model are discussed in this paper. The experimental data highlights an impact of propeller locations on lift, drag, moment and vortex system of the UAV. The results also showed that the propeller advance ratio, J influence the vortex system above UAV wing.

Kasler, Y., Rahm, S., Simmet, R. and Kuhn, M.

"WAKE MEASUREMENTS OF A MULTI-MW WIND TURBINE WITH COHERENT LONG-RANGE PULSED DOPPLER WIND LIDAR"

Journal of Atmospheric and Oceanic Technology, Vol. 27, September 2010, pp. 1529-1532. 47.

Long-range Doppler wind light detection and ranging (lidar) measurements at a wind turbine were carried out for the first time. The turbine was of the type Areva M5000 and is located at a site near the coastline in Bremerhaven, in the northern part of Germany. This wind turbine is the prototype for the German offshore test site 'alpha ventus' and has a rated power of 5 MW. Information about the ambient wind field before and after this multimegawatt wind turbine was obtained. In this paper the measurement technique is discussed and the results of measurements in the diurnal layer and in the stable nocturnal boundary layer are shown. The main focus of this work is to determine the reduction of the wind speed at certain distances downstream from the rotor.

Kasper, S., Burke, T., Rapski, J. and Saneholtz, N.

"AERODYNAMICS OF FORMATION FLIGHT FOR UAVS"

AIAA Paper 2016-1285, January 2016, San Diego, CA.

The upwash generated from wingtip vortices from a lead aircraft can be utilized by a suitably positioned trailing aircraft to obtain essentially 'free' lift. This free lift means it requires a smaller angle of attack to maintain altitude, thus reducing drag, which in turn leads to reduced fuel consumption and increased range and endurance. The unmanned aspect of a UAV relieves safety constraints that exist with human flight. In particular, unmanned aircraft can fly closer to other vehicles, thus benefitting from the stronger vortices closer to the lead aircraft. This idea was expanded to combine the upwash of two leading aircraft positioned side by side, such that the counter rotating vortices will have sections of upwash that coincide with each other and will therefore be stronger than the upwash from only one leading aircraft. This project measured the effects that the combined vortices have on the trailing UAV and compared those results to a similar test with only one lead aircraft. This project includes both an experimental and a computational study of vortex effects. Experimental lift and drag measurements of the trailing vehicle were taken in a wind tunnel at varying trailing distances, using both one and two leading wings. The wings were concurrently modeled and evaluated in ANSYS Fluent at wind tunnel conditions. Wind tunnel results were used to validate computational results at wind tunnel conditions, and then the computational study was expanded to actual cruise conditions.

Kato, H., Koike, S. and Nakakita, K.

"TIME-RESOLVED STEREOSCOPIC PIV MEASUREMENT OF UNSTEADY WINGTIP FLOWFIELD"

AIAA Paper No. 2012-0035, January 2012, Nashville, Tennessee.

Time-Resolved Particle Image Velocimetry (TR-PIV) which can measure velocity fields at sampling rate of 10 kHz or higher sampling rate is now widely applied to practical flow problems. The TR-PIV provides the two-dimensional distributions of the spectrum of the velocity fluctuation because it can measure the two-dimensional velocity distributions at high sampling rate. But flow fields in industrial wind tunnel applications are three dimensional. Three-dimensional velocity measurement is strongly needed. The objective of this research is to develop time-resolved stereoscopic PIV system for industrial wind tunnels and to apply the system to unsteady wingtip flow field on a single rectangular wing. The objective flow fields are unsteady, not uniform, and strongly influenced by a probe. Generally, it is difficult to measure such unsteady velocity fields. For example, hot wire anemometer which is widely used for unsteady velocity measurement is not suitable for the objective flow field due to the intrusiveness. The time-resolved stereoscopic PIV can measure such flow fields precisely because it is not intrusive. Thus, the time-resolved stereoscopic PIV is suitable to investigate the objective flow fields. Time-resolved stereoscopic PIV system was developed for industrial wind tunnel testing. Unsteady wingtip velocity field was measured by the time-resolved stereoscopic PIV system in JAXA 2m x 2m low-speed wind tunnel. The wingtip vortices behavior of NACA0012 rectangle wing model was investigated. Finally, the power spectrum density distributions of the velocity fluctuation were shown

to clarify the vortex behavior and to demonstrate the effectiveness of the time-resolved stereoscopic PIV data to specify the unsteady flow phenomena.

Kato, H., Shimoyama, K., Obayashi, S. and Kudo, M.

"DATA MINING FOR THE ADVECTION DATABASE OF WAKE VORTICES"

AIAA Paper No. 2010-7989, Toronto, Canada, August 2010.

Advection database of wake vortices was constructed based on the Doppler lidar measurements at Sendai Airport to understand the relations among measurement, weather factors and behavior of wake vortex. The advection database of wake vortex consists of three measurement factors and fifteen weather factors as variables to determine the wake vortex behavior. However, the extraction of correlations from the high-dimensional data is difficult in general. Therefore, in this paper, data mining was employed as an efficient approach to extract relations among the variables from the advection database of wake vortex. As a first step of the data mining, redundant measurement, weather factors were removed through Spearman rank method, then Self-Organizing Map was created to find correlations among the measurement, weather factors and wake vortex behavior. Next, the measurement, weather factors which have larger influences to the behavior of the wake vortex were identified by Analysis of Variance. Finally, rough set theory revealed the specific rules of measurement, weather factors to determine wake vortex behavior.

Kato, N., Ohkuma, T., Kim, J. R., Marukawa, H. and Niihori, Y.

"FULL SCALE MEASUREMENTS OF WIND VELOCITY IN TWO URBAN AREAS USING AN ULTRASONIC ANEMOMETER"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 41, 1992, pp. 67-78.

This paper describes the results obtained from the measurements of the characteristics of wind turbulence in urban areas using ultrasonic anemometers. The data used in this paper is what which was gained from the year-long observation extending from January 1990 through December 1990 and during two typhoons No. 8922 and No. 9011. The values of the turbulence intensity at a height of less than 100m were approximately 10 15 percent larger than those recommended for corresponding urban areas by the AIJ standard, in which the specified power index of the wind profile is set at 0.3. The shape of the power spectral density for the u component agrees fairly well with the shape of the Karman type spectrum. The power spectral density of the v component is quite similar to the Karman type spectrum for the u component.

Katz, J.

"CLASSICAL AND POTENTIAL-FLOW AERODYNAMICS DO WE NEED THEM?"

AIAA Paper 2019-0864, January 2019, San Diego, CA.

Nowadays, computational tools for solving the flow over complex objects are widely available and easily connected to basic design tools. This allows iterative engineering analysis and design without using classical ideal flow models. Furthermore, most of the classical solutions rely on complex, and often lengthy, mathematical formulation, not very exciting when presented in the classroom. However, those simple models were successful in predicting many important features of the flow-field, as in the case of the flow over wings. On the other hand, efforts to reduce graduation times, forced curriculum planners to reevaluate the need for teaching classical aerodynamics. In the following discussion, an effort is made to explain why those methods work, what are the resulting conclusions, and respond to the frequently asked question about the method convergence and validation. Also, when educating engineers, simple models (e.g., ideal flow models) are needed to predict design trends and thereby shortening preliminary design cycles.

Katz, J. and Galdo, J. B.

"EFFECT OF ROUGHNESS ON ROLLUP OF TIP VORTICES ON A RECTANGULAR HYDROFOIL"

Journal of Aircraft, Vol. 26, No. 3, March 1989, pp. 247-253

Experiments focusing on the development of a tip vortex on a rectangular NACA-66 hydrofoil have been performed in a towing tank. The study consists of flow visualization by illuminating with a laser sheet and by disturbing fluorescing dye in the water. It also includes surface pressure measurements, particularly around the tip. The experiments have been performed with a smooth surface, and by painting a layer of roughness elements with characteristic sizes of 250 and 500 micron. The observations demonstrate that the physical dimensions of the tip vortex are not affected significantly by the surface roughness, whereas the surface pressure, particularly just under the tip vortex, changes substantially. This observation leads to the conclusion that an increase in the surface roughness reduces the strength of the tip vortex. The flow visualization experiments also demonstrate that for all the roughness sizes, the tip vortex dimensions increase with the incidence angle and decreases as the velocity is increased. In addition, the study demonstrates that the flow is unsteady and that the tip region is dominated by multiple secondary vortex structures. A series of sample photographs demonstrating these phenomena is provided.

Katz, J. and Maskew, B.

"UNSTEADY LOW-SPEED AERODYNAMIC MODEL FOR COMPLETE AIRCRAFT CONFIGURATIONS"

Journal of Aircraft, Vol. 25, No. 4, April 1988, pp. 302-310.

A method for converting steady-state, potential-flow based panel methods into a time-dependent mode is derived and applied to several test cases. For this development, an improved vortex wake model was constructed that was also suitable for simulating the leading-edge separation of slender wings at high angles of attack. Computed flow-field simulations are presented for various unsteady and

high-angle-of-attack conditions, involving geometries such as simple wings, rotors, and complete aircraft configurations.

Katz, J. and Weihs, D.

"BEHAVIOR OF VORTEX WAKES FROM OSCILLATING AIRFOILS"

J. Aircraft, Vol. 15, No. 12, December 1978, pp. 861-863

The vortex wake of an oscillating airfoil has long been studied, and it is now well known that under certain conditions strong nonlinear interactions can develop. This appears in the form of agglomerations of vortex elements resulting in discrete concentrations of vorticity which can then be analyzed as separate vortices. In this Note, we present a simple and rapid numerical technique for calculation of the time-dependent growth and evolution of wakes. The parameters influencing the rollup are examined and the ranges of reduced frequencies for which such instabilities occur are determined.

Katz, S. L., Hudson, B., Pschunder, H., Lupnacca, J. D. and Marshall, R. E.

"AIRCRAFT WAKE VORTEX DETECTION TRIALS WITH C-BAND INSTRUMENTATION RADAR"

Twenty-eighth Conference on Radar Meteorology, Austin, TX, September 7-12, 1997, Preprints, American Meteorological Society, 1997, pp. 163-164

Detection of wingtip vortices by radar in a range of weather conditions is desirable. Experimental trials have been conducted by the FAA to identify the most reliable techniques for discriminating wingtip vortex radar echoes from wind-generated echoes; attention was given to the dependence of vortex signatures on flow orientation relative to the radar beam and aircraft altitude.

Katzoff, S. and Sweberg, H. H.

"GROUND EFFECT ON DOWNWASH ANGLES AND WAKE LOCATION"

NACA TR-738, 1942, NACA Langley Aero. Lab., Langley Field, VA

A theoretical study was made of the reduction in downwash and the upward displacement of the wake in the presence of the ground, and some verification of theory was obtained by means of air-flow measurements made with a ground-board and image-wing combination. Methods are given for estimating the effects and numerous examples are included to illustrate the nature of these effects and to show their order of magnitude.

Kauertz, S.

"THE CREDOS PROJECT. SAFE SEPARATION DISTANCES FOR TAKE-OFF AND DEPARTURE: EVALUATION OF MONTE CARLO BASED SAFETY ASSESSMENT RESULTS"

D3-10, November 2009.

This document contains the results of a safety assessment with regard to wake vortex encounter risk during departure using the combination of the tools WakeScene-D and VESA-D. The encounter probability and risk is assessed for several scenarios in comparison considering the effect on the encountering aircraft. Based on the relative encounter risk for different crosswinds and separations a crosswind threshold is derived which could allow a safe reduction of separations during departure.

Kauertz, S.

"THE CREDOS PROJECT: WORK PACKAGE 3 FINAL REPORT"

D3-11, November 2009.

The present document contains the final report of CREDOS work package 3 'Risk Modelling and Risk Assessment' summarizing the main results from the different tasks and giving an overview on the produced documentation.

Kauertz, S. and Neuwerth, G.

"EXCITATION OF INSTABILITIES IN THE WAKE OF AN AIRFOIL WITH WINGLETS"

AIAA Paper No. 2006-3470, San Francisco, CA, June 2006

This paper describes experimental investigations of possibilities to destabilize the vortex wake behind an airfoil by using winglets with integrated rudders. These rudders can be deflected statically, as well as oscillated periodically around their static deflection. The oscillation is intended to excite short-wavelength instabilities inherent in the vortex system to provoke an accelerated decay of the vortices. The used model also comprises deflectable ailerons and can be equipped with a pair of trailing edge flaps to modify the vortex system. Quantitative wake investigations by Particle Image Velocimetry have been conducted up to 43 spans behind the wing model in a water towing tank. Results show a markedly earlier decay of the vortex system and abatement of induced rolling moments in the wake for certain rudder configurations in comparison to the clean airfoil configuration. However, the oscillation of the winglet rudders did not lead to a further acceleration of vortex decay compared to the statical case in the frame of the experiments conducted here.

Kauertz, S. and Neuwerth, G.

"EXCITATION OF INSTABILITIES IN THE WAKE OF AN AIRFOIL BY MEANS OF ACTIVE WINGLETS"

Aerospace Science and Technology, Vol. 10, 2006, pp. 551-562.

Strong wake vortices that develop behind every aircraft as a byproduct of lift production pose a threat where aircraft fly in close staggering such as in the vicinity of airports. One approach to alleviate these vortex wakes is the use of high lift systems or control surfaces of the wing to create an unstable vortex system. The inherent instability of this vortex system shall then lead to an accelerated decay of the vortex wake, triggered for example by a periodic motion of the control surfaces. In the work presented here a simple wing model with winglets able to produce a vortex system of up to six distinct vortices is investigated in towing tank experiments. Theoretical studies show that these vortex systems potentially have a high degree of instability. By means of active oscillation of rudders integrated into the winglets, these vortex systems are to be excited to initiate an accelerated decay of the vortices. It is shown that configurations exist which exhibit strong instabilities, that lead to a significantly lower hazard level behind the vortex generating wing, even when not actively excited. However, an additional oscillation does not seem to accelerate decay of these vortex systems in relation to the statistical reference case.

Kauertz, S., Holzaepfel, F. and Kladetzke, J.

"WAKE VORTEX ENCOUNTER RISK ASSESSMENT FOR CROSSWIND DEPARTURES"

Journal of Aircraft, Vol. 49, No. 1, January-February 2012, pp. 281-291.

In the European research project, CREDOS (Crosswind-Reduced Separations for Departure Operations), the feasibility of a concept for reduced wake turbulence separations upon departure in crosswind conditions has been investigated. The safety assessment of this concept includes risk assessment with respect to wake vortex encounters. This paper describes the methodology developed for this assessment and its application during the project. The methodology employs two simulation tools, the Wake Vortex Scenarios Simulation Package for Departures (WakeScene-D) and the Vortex Encounter Severity Assessment for Departure (VESA-D), which are extensions of existing tools related to the departure flight phase. WakeScene-D primarily determines the frequency of wake encounters, whereas VESA-D estimates the severity of these encounters. Both can be combined to quantify and compare wake encounter risk for various departure scenarios. In the risk assessment, departures with variable aircraft separations and varying crosswind conditions were investigated to determine which crosswind level is necessary to suspend wake-turbulence-related separations during departure without degrading safety. Monte Carlo simulations have been conducted comparing medium and heavy aircraft type departures with 2 min. of separation to departures with a separation of 1 min. under varying crosswind strengths. The results not only give an indication of which crosswind magnitudes could be sufficient to safely suspend wake-turbulence-related separations upon takeoff, but they also reveal significant influences, such as the departure route layout and the change of wind direction with altitude, on wake encounter risk.

Kawachi, K.

"EXTENSION OF LOCAL MOMENTUM THEORY TO HOVERING ROTOR WITH DISTORTED WAKE"

Journal of Aircraft, Vol. 19, July 1982, pp. 538-545

The local momentum theory is extended to include the effects of a rotor wake deformation in hovering flight. A comparison of this extended local momentum theory with a prescribed wake vortex theory is presented. The results indicate that the extended local momentum theory has the capability of achieving a level of accuracy like that of the prescribed wake vortex theory, using a much smaller amount of computer time. It is also shown that the analytical results obtained using either theory are in reasonable agreement with experimental data.

Kawahara, G.

"ENERGY DISSIPATION IN SPIRAL VORTEX LAYERS WRAPPED AROUND A STRAIGHT VORTEX TUBE"

Physics of Fluids, Vol. 17, May 2005, pp. 055111-1 to 055111-13

Energy dissipation in spiral layers of high azimuthal vorticity around a straight vortex tube is investigated analytically. Asymptotic expressions of local and total viscous dissipation are obtained for the spiral vortex layers. When a vortex tube, which aligns with a uniform shear flow of a shear rate S , starts with a vortex filament of circulation at an initial instant $t=0$, it wraps and stretches background vorticity lines around itself to form double spiral vortex layers of intense dissipation.

Kawanishi, H. and Lan, C. E.

"A NUMERICAL STUDY OF WAKE ROLL-UP FOR A FLAPPED TRANSPORT WING"

AIAA Paper No. 1997-2332, Atlanta, Georgia, June 1997

Results of wake roll-up from an isolated transport-type wing at a low subsonic speed calculated using the thin-layer Navier-Stokes method are presented. The computational results indicate that the vortex roll-up and its decay are faster for the flap-deployed case than for the clean configuration as indicated in experimental data. The tip vortex is stronger for the clean configuration than for the flapped case. The computed location of the trailing vortex for the clean configuration is near the mid-semispan where flow separation occurs, and more inboard than that behind a rectangular wing. On the other hand, the trailing vortex for a flapped configuration at the same or higher lift coefficient as the clean configuration tends to be more outboard, depending on the spanwise location of the partial span flap. For a flap span with the outer edge near the mid-semispan, the outboard flap vortex merges with the trailing vortex within half span length. On the other hand, if the location of the flap outer edge is more inboard, the outboard flap vortex is still distinct even at 7.5 span lengths downstream. The condition for merging appears to be the continuity of the wake vorticity distribution near the trailing edge.

Kazakov, A. V.

"STABILITY OF AN AXISYMMETRIC SWIRLED FLOW IN A SUPERSONIC COCURRENT STREAM FOR VOLUME ENERGY SUPPLY IN THE VISCOUS VORTEX CORE"

Fluid Dynamics, Vol. 40, No. 1, 2005, pp. 62-70

The results of numerical calculations of the stability of axisymmetric swirled flows in a viscous vortex embedded in a supersonic concurrent stream with a constant circulation of the azimuthal velocity component are presented. The stability characteristics of the swirled three-dimensional viscous flow in the streamwise vortex are determined based on the linearized system of Navier-Stokes equations for a viscous heat-conducting gas under the assumption that the basic undisturbed flow is locally plane-parallel. The disturbed flow stability is studied in the temporal formulation with respect to both symmetric and asymmetric three-dimensional waves traveling along the vortex axis and corresponding to both positive and negative values of the azimuthal wavenumber. It is shown that at external inviscid flow Mach numbers thermal energy supply in a small region near the vortex axis leads to considerable restructuring of the basic undisturbed flow in the vicinity of the vortex core, the growth of the adverse pressure gradient along the vortex axis, and a significant change in the small perturbation stability and behavior.

Kazakov, A. V.

"EFFECT OF VOLUME ENERGY SUPPLY ON THE STABILITY OF A SUBSONIC VORTEX FLOW"

Fluid Dynamics, Vol. 38, No. 4, 2003, pp. 552-560

Calculations of the stability of an axisymmetric vortex flow of viscous heat-conducting gas with volume energy supply are presented. The unperturbed axisymmetric vortex flow was found numerically using a quasi-cylindrical approximation of the Navier-Stokes equations under the assumption of constant peripheral-velocity circulation in the ambient co-current flow. The volume energy supply in the viscous vortex core was modeled by an additional source term in the energy equation. The stability characteristics of the viscous vortex flow in a longitudinal vortex with respect to both axisymmetric and non-axisymmetric three-dimensional waves traveling along the vortex axis and corresponding to both positive and negative values of the azimuthal wave number were found using the time-dependent formulation of the linear stability theory for compressible three-dimensional plane-parallel flows.

Kazarin, P. S. and Golubev, V. V.

"COMPARISON OF PROBABILISTIC APPROACHES FOR PREDICTING THE CONE OF UNCERTAINTY IN AIRCRAFT WAKE VORTEX EVOLUTION"

AIAA Paper 2017-4369, June 2017, Denver, CO.

The paper presents evaluation of the fast-time probabilistic wake-vortex evolution models implemented as part of the Wake Vortex Safety System (WVSS) code to be employed in the wake safety risk analyses by FAA SSMT program. The validation of obtained predictions against LIDAR data collected at Memphis and Denver airports in 1995 and 2003 is conducted to estimate the accuracy and ranges of uncertainty in the wake vortex propagation models. In particular, probabilistic wake evolution predictions based on Monte-Carlo simulations are compared against results based on P2P

and RMS approaches to examine and compare the cones of uncertainty in the wake evolution. The comparison with results obtained using several previously developed models is also presented.

Kazarin, P. S. and Golubev, V. V.

"ON EFFECTS OF GROUND SURFACE CONDITIONS ON AIRCRAFT WAKE VORTEX EVOLUTION"

AIAA Paper 2017-4368, June 2017, Denver, CO.

The paper investigates and compares decay and transport of an aircraft wake vortex in the vicinity of a solid surface, a forest canopy, and a water surface, representative of various terminal-zone environments. The analysis elucidates some critical features and differences in near-ground wake dynamics which could be important for aircraft operations during takeoff and landing. Particularly, the results of the study may provide insights for ensuring wake safety in future integration of various classes of unmanned aircraft systems (UAS) in airport operations. The reported results are based on Large Eddy Simulations (LES) conducted using an open-source OpenFOAM solver. The obtained high-fidelity findings will form the basis for reduced-order models to be integrated in the fast-analysis code under development for in-situ wake vortex evolution predictions.

Kazarin, P. S. and Golubev, V. V.

"HIGH-FIDELITY SIMULATIONS OF TERMINAL-ZONE HETEROGENEOUS TERRAIN EFFECTS ON AIRCRAFT WAKE VORTEX EVOLUTION"

AIAA Paper 2018-1279, January 2018, Kissimmee, FL.

The current work is an extension to the previous study where the wake vortex propagation in the vicinity of a solid surface, a forest canopy and a water surface was studied. The effects of different configurations of forest canopy on aircraft wake vortex transport and decay are addressed in detail in this paper. The temporal 3D LES simulations using OpenFOAM solver are performed for fully rolled-up vortices corresponding to a generic heavy aircraft. The numerical setup is validated with the experimental data from the water filled tow-tank. Different types of the forest canopy specified in terms of various shapes and physical characteristics are employed with the wake evolution results compared. The obtained predictions will be integrated in the reduced order models under development for fast-time wake vortex analysis.

Kazarin, P., Golubev, V., Provalov, A., Borener, S. and Hufty, D.

"A VARIABLE-FIDELITY APPROACH TO WAKE SAFETY ANALYSIS IN THE CONTEXT OF UAS INTEGRATION IN THE NAS"

AIAA Paper 2016-3452, June 2016, Washington, DC.

The paper presents results of the wake vortex safety analysis conducted for selected unmanned aircraft systems (UAS) operating alongside commercial aircraft in the terminal zone. The approach is

developed based on a dynamic model of an aircraft entering an upstream wake vortex that allows evaluating changes in the important aerodynamic parameters following the wake vortex interaction and assessing the operational safety risks in application to variable-size UAS. The employed variable-fidelity approach integration reduced-order models of wake generation, evolution and interaction incorporating both theoretical and high-fidelity predictions. The benchmark parametric study estimates UAS responses in terms of the roll control ratios (RCR) developed by the follower aircraft depending on their position and orientation relative to the wake shed by the leader B-737 aircraft, as well as the duration of the wake-UAS interaction. The UAS dynamic reaction is examined in the context of several possible flight control scenarios that include a time-delayed maximum aileron deviation.

Kazarin, P., Provalov, A., Golubev, V., Borener, S., Hafty, D., Crook, I. and Suchkov, A.

"TERMINAL-ZONE WAKE VORTEX SAFETY ASSESSMENT IN THE CONTEXT OF UAS INTEGRATION IN THE NAS"

Transportation Research Procedia, Vol. 14, 2016, pp. 1364-1373.

The paper presents results of the wake vortex safety analysis conducted for selected unmanned aircraft systems (UAS) operating alongside commercial aircraft in the terminal zone. The approach is developed based on a dynamic model of an aircraft entering an upstream wake vortex that allows evaluating changes in the important aerodynamic parameters following the wake vortex interaction and assessing the operational safety risks in application to variable-size UAS. The benchmark parametric study estimates UAS responses in terms of the roll control ratios (RCR) developed by the follower aircraft depending on their position and orientation relative to the wake shed by the leader B737 aircraft, as well as the duration of the wake-UAS interaction. The UAS dynamic reaction is examined in the context of several possible flight control scenarios that include a time-delayed maximum aileron deviation and application of a robust feedback-loop flight controller.

Ke, G., Li, W. and Zheng, Z. C.

"VORTEX SCATTERING EFFECTS ON ACOUSTIC WAVE PROPAGATION"

AIAA Paper 2015-3267, June 2015, Dallas, TX.

In this paper, the Euler equation model is used to investigate sound wave propagation over subsonic vortices. The cases of a single vortex, a pair of counter-rotating stationary vortices, and the moving vortex pair under the mutual induction velocity are studied. The numerical scheme uses a high-order WENO scheme to accommodate the highly convective background flow at high Mach numbers. The simulation results are compared with the analytical solutions and literature data with good agreement achieved. The scattering effects of the vortices and the related scaling laws are discussed.

Keane, M., Buckton, D. and Darracq, D.

"WAKE VORTEX HAZARD DETECTION DOPPLER LIDAR"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

The performance of an airborne wake vortex detection system is investigated by simulation. The proposed detection system uses a forward looking, pulsed Doppler Lidar to interrogate the intended flight path of the aircraft. It aims to give advance warning of any hazardous wake vortices, generated by preceding aircraft, that enter the aircraft's intended airspace. Any Doppler system is only capable of resolving velocities in the direction of the emitted wave. Thus, the proposed system aims to detect hazardous wake vortices based on axial characteristics. Realistic wake vortices are simulated in a convective atmospheric boundary layer using a three-dimensional Large Eddy Simulation model. The simulation is initialized with data collected during trials made at Idaho Falls by the Federal Aviation Administration in 1990. The evolution of the vortices in characteristic atmospheric conditions is then calculated. At discrete stages in the evolution, the computed flow field is applied to the Lidar system simulator. The Lidar system simulator models the shot noise limited Lidar, the atmosphere, and the signal processing, outputting the set of line-of-sight velocities that would be measured by a Doppler Lidar interrogating the given flow field. Pattern recognition techniques are used to detect any vortices. At each stage the hazard posed by any vortex in the flow field is estimated by calculating the rolling moment that it would produce on an encountering aircraft. If this rolling moment is of the same order as the rolling-moment capability of a commercial transport aircraft, then it is classified as a hazardous vortex. This paper aims to demonstrate that all such hazardous vortices can be detected using the proposed Lidar system.

Keane, M., Buckton, D., Redfern, M., Bollig, C., Wedekind, C. and Kopp, F.

"AXIAL DETECTION OF AIRCRAFT WAKE VORTICES USING DOPPLER LIDAR"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 850-861

The real-time detection of aircraft wake vortices has become an important part of studies aimed at increased runway productivity. A processing approach is presented, which has been used to detect wake vortices from an axial point of view with a Doppler lidar system. The performance of the processing approach is investigated using simulation techniques. In addition, the effectiveness of the approach is demonstrated using data from a series of wake vortex measurement experiments carried out at Toulouse airport in March 2000. Robust axial detection of wake vortices with a Doppler lidar system has been achieved at ranges between 400 m and 2 km. Sample results for Airbus A340- and Airbus A320-generated wake vortices are presented.

Kedzie, C. R. and Griffin, K. E.

"EXPERIMENTAL MEASUREMENTS OF WAKE CHARACTERISTICS OF LOW ASPECT-RATIO DELTA AND FLAPPED-PLATE PLANFORMS"

Technical Note USAFA-TN- 83-6, March 1983, US Air Force Academy, Colorado Springs, CO.

This report documents the characteristics and location of the wakes for two generic lifting surface planforms. The geometric description locates these wakes as they develop downstream from a low

aspect-ratio delta wing and a bent-plate wing. The wakes are graphically depicted at several streamwise locations downstream of these wings with accompanying cross-velocity vector plots to assist in interpreting them. The data used to determine these wake characteristics was obtained by surveying the wings' flow field with a seven-hole pressure probe.

Keeffe, B. E.

"VORTEX ADVISORY SYSTEM SIMULATION OF CHICAGO O'HARE INTERNATIONAL AIRPORT"

FAA-RD-78-76, July 1978, FAA NAFEC, Atlantic City, NJ

This report evaluates, in simulation, the procedural implications of the Vortex Advisory System (VAS) on the Chicago O'Hare terminal air traffic control environment. It also attempts to demonstrate any cost benefits/capacity gains which may accrue using reduced VAS aircraft separation criteria on the final approach course based upon meteorological assurance of vortex dissipation. Utilizing the National Aviation Facilities Experimental Center (NAFEC) Digital Simulation Facility (DSF), a real-time simulation of the Chicago O'Hare International Airport airside operations was conducted between March 28 and June 24, 1977. There were 105 data runs of 1 hour and 20 minutes duration completed during this period. Test results indicate that (1) no procedural implications emerged which would deter the implementation of VAS at Chicago O'Hare Airport, and (2) arrival rate increases are sufficient to support previous cost/benefit analysis studies.

Keime, M., Koop, L., Ehrenfried, K. and Dillmann, A.

"A 2 D VORTEX SHEET MODEL OF THE FLAP SIDE EDGE FLOW"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

Airframe noise contributes significantly to the total sound radiated during approach. One important noise source is located at the side-edge of the extended wing-flaps. Shear layers emerge at the sharp corners of the side-edge and roll up into a vortical structure. Nonstationarity of this structure leads to pressure fluctuations at the rigid surface and thus to sound radiation into the far field. The objective of the present study is to displace or destroy the vortical structure by blowing air into the vortex, thus leading to a reduction of sound emission. The feasibility of this method of flow control has been shown experimentally. In order to further optimize the configuration of the experimental setup and to investigate the physical mechanism in detail, a two-dimensional potential flow model is developed.

Keller, J. D., McKillip Jr, R. M. and Wachspress, D. A.

"PHYSICAL MODELING OF AIRCRAFT UPSETS FOR REAL-TIME SIMULATION APPLICATIONS"

AIAA Paper No. 2008-6205, August 2008, Honolulu, HI.

Improving the understanding of flight dynamics and control response characteristics of aircraft in upset conditions has been the focus of extensive research and development in recent years. Aircraft

may experience upsets due to many factors, and without suitable corrective actions, upsets may ultimately lead to loss of control accidents. To provide models for engineering analysis and pilot training, conventional simulation approaches have historically used multi-variable aerodynamic databases (look-up tables) derived from wind tunnel and/or flight test data, which are difficult to acquire and do not always encompass the desired flight envelope. An alternative approach for modeling aerodynamic and flight dynamic characteristics of aircraft in upset conditions has been investigated based on methods that are not data-driven but that are derived from physically-based models. This paper describes a modeling approach based on nonlinear lifting line/strip theory analysis of the aerodynamic loads combined with an unsteady, freely-evolving vortex wake model for the induced velocity due to the lifting surfaces. The paper describes background work and recent developments toward a generic, physically-based model for aircraft upsets. Application of the modeling approach to unmanned aircraft is presented.

Keller, J. J.

"THE EFFECTS OF NON-UNIFORM DENSITY AND STAGNATION PRESSURE ON THE BREAKDOWN CHARACTERISTICS OF A VORTEX"

Z. angew Math Physics, Vol. 45, 1994, pp. 347-370.

This paper is concerned with the extension of the theory of vortex breakdown, that was presented in previous publications by the present author and others, to cases of non-uniform density and non-uniform stagnation pressure outside the vortex core. The effects of radial density and velocity variations play an essential role for the layout of modern low-emission burners for premixed combustion. Furthermore, these effects turn out to be important with respect to an improved understanding of the formation of zones of flow recirculation in tornado-like vortices. With the help of the extension of a variational principle for axisymmetric flow to the case of non-uniform density it is possible to discuss inviscid flows of non-uniform density and stagnation pressure in great generality. A numerical solution method is given for general axisymmetric vortex flows, including flows that undergo vortex breakdown. The influences of density and stagnation pressure variations on vortex breakdown are analyzed in detail, for the special case of a generalized Rankine vortex. It is found that a radially increasing density leads to a reduction of the swirl number at which vortex breakdown occurs, whereas a radially decreasing axial velocity component in the approach flow of a vortex breakdown bubble leads to a substantially enlarged bubble. Finally, a Richardson number criterion is proposed for the scaling of a vortex breakdown bubble in a tornado.

Keller, J. J.

"ON THE INTERPRETATION OF VORTEX BREAKDOWN"

Phys. Fluids, Vol. 7, No. 7, July 1995, pp. 1695-1702

Studying the numerous papers that have appeared in the recent past that address 'vortex breakdown' it may be difficult for a reader to avoid getting rather confused. It appears that various authors or even

schools have conflicting views on the correct interpretation of the physics of vortex breakdown. Following the investigation by Keller et al. (1985), in this paper, axisymmetric forms of vortex breakdown, as originally defined by Benjamin (1962) are addressed. It is argued that at least some of the previous investigations have been concerned with different aspects of the same phenomena and may, in fact, not disagree. One of the most fundamental questions in this context concerns the properties of the distributions of total head and circulation on the downstream side of vortex breakdown transitions. Some previous investigators have suggested that the downstream flow would exhibit properties that are similar to those of a wake. For this reason, the phenomenon of vortex breakdown is investigated for a class of distributions of total head and circulation in the domain of flow reversal that is substantially more general than in previous investigations. Finally, a variety of problems are discussed that are crucial for a more complete theory of vortex breakdown, but have not yet been solved. It is shown that for the typically small flow speeds in a domain of flow reversal produced by a vortex breakdown wave, the departures of both vortex core size and swirl number, with respect to the case of uniform total pressure in the zone of flow reversal, as discussed by Keller et al. (1985), remain surprisingly small. As a consequence, the possible appearance of large departures from a Kirchhoff-type wake must be due to viscous diffusion at low and due to shear-layer instabilities at high Reynolds numbers.

Keller, J. J.

"ON THE PRACTICAL APPLICATION OF VORTEX BREAKDOWN THEORY TO AXIALLY SYMMETRICAL AND THREE-DIMENSIONAL COMPRESSIBLE FLOWS"

Phys. Fluids, Vol. 6, No. 4, April 1994, pp. 1515-1523

A perfect-fluid theory for axially symmetrical vortex breakdown flows by Keller et al. is extended to three-dimensional compressible flows. In a first step, an approximate theory for thin vortex cores is compared to the exact theory for axially symmetrical flows of inviscid, incompressible fluids. In subsequent steps, the approximation for thin vortex cores is extended to flows of compressible fluids that are not axially symmetrical. Finally, the various types of vortex breakdown flows and the shear layer instabilities at the surface of vortex breakdown bubbles are briefly discussed.

Kelly, A. J. and Handelsman, M.

"ELECTROMAGNETIC EFFECTS OF AIRCRAFT WAKE-ACTIVE FEUILLET INTERACTION"

IEEE Trans. Aerospace and Electronic Systems, Vol. AES-10, January 1974, pp. 136-143

A mechanism by which an aircraft wake can interact strongly with the electromagnetic radiation present in an active elevated anomalous refractivity region (active Feuillet) is analyzed. The aircraft wake structure, assumed to consist of twin contrarotating vortices plus entrained irrotational gas, trailing behind the wings of typical large aircraft is shown to be capable of descending approximately 3 wing span distances and attaining a length of the order of 10 km, prior to instability-induced disruption. The parcel of air such a descending coherent wake structure can convey into an active Feuillet is

demonstrated to alter significantly the local refractive index of the duct and induce substantial radiation spillage. The general characteristics of the electromagnetic radiation produced by this interaction process (i.e., scattering by diaphanous objects) is described.

Kenig, C. E., Ponce, G. and Vega, L.

"ON THE INTERACTION OF NEARLY PARALLEL VORTEX FILAMENTS"

Comm. in Math. Phys., Vol. 243, 2003, pp. 471-483

The system for the interaction of nearly parallel vortex filaments deduced by Klein, Majda and Damodaran is considered. Local existence for the associated initial value problem with data which are small perturbations of perfect parallel filaments is proved. Assumptions on the unperturbed configurations and on the initial parameters which guarantee the existence of global regular solutions (no finite time collapse) are deduced.

Kenwright, D. N. and Haimes, R.

"AUTOMATIC VORTEX CORE DETECTION"

IEEE Computer Graphics and Applications, July-August 1998, pp. 70-74

An eigenvector method proves effective for extracting and visualizing features such as vortex cores. Incorporated in a finite-element flow solver, the algorithm guides automatic mesh refinement.

Kerlick, G. D.

"VISUALIZATION FOR AERODYNAMIC DESIGN OF HELICOPTER ROTOR BLADES"

Proceedings of the IEEE Conference on Visualization - 'Visualization '95', October 29 - November 3, 1995, pp. 351-354.

Visualization, animation, and simulation techniques are applied to the problem of rotor design for helicopters. Periodic unsteady experimental velocity data (laser Doppler velocimetry or LDV) in two dimensions and velocity data derived from simulated vortex systems in three dimensions are compared using the same visual tools. Animations show the development of rotor wake systems and induced velocities over time. Modified particle trace integration schemes are used to calculate steady streamlines and unsteady particle paths for both kinds of data. In an extension of this work, a virtual environment system was used to view the wake vortex system and an interactive probe was used to explore the induced velocity field. Future work will enable interactive visual debugging and simulation steering.

Kerr, T. H. and Dee, F. W.

"A FLIGHT INVESTIGATION INTO THE PERSISTENCE OF TRAILING VORTICES BEHIND LARGE AIRCRAFT"

ARC Report CP-489, September 1959, Royal Aircraft Establishment, Farnborough, England. (Also, RAE Tech. Note Aero. 2649.)

A flight investigation into the persistence of trailing vortices has been made by flying a Devon in the wake of a Lincoln. The tests were made in the clean and flaps down configurations. The results indicate that the disturbance decays rapidly after 160 seconds and 105 seconds, respectively, and produces negligible rolling moments after 190 seconds and 120 seconds, respectively. The flight results have been compared with the available theoretical work and the comparison suggests that the theory of Squire holds until the vortices start to decay rapidly.

Kevlahan, N.

"GEOMETRIC, STOCHASTIC AND ALGEBRAIC VORTICES"

In *Vortex Dominated Flows*, edited by D. Blackmore, E. Krause and C. Tung, 2005, World Scientific, New Jersey, Chapter 6, pp. 99-118.

Mathematical concepts can often be understood in one of three complementary ways: geometric, algebraic, or stochastic. In this chapter I show how vortices may be interpreted in each of these three ways. Each point of view is appropriate for certain applications, and each sheds new light on the role played by vortices in fluid dynamics. This review is necessarily brief, and makes no attempt to be exhaustive, but I hope it gives an interesting overview of vortices in all their forms.

Kevlahan, N. K.-R.

"STOCHASTIC DIFFERENTIAL EQUATION MODELS OF VORTEX MERGING AND RECONNECTION"

Physics of Fluids, Vol. 17, No. 6, June 2005, 065107-1-065107-11

We show that the stochastic differential equation (SDE) model for the merger of two identical two-dimensional vortices proposed by Agullo and Verga ['Exact two vortices solution of Navier-Stokes equation' *Phys. Rev. Lett.*, 78, 2361 (1977)] is a special case of a more general class of SDE models for N interacting vortex filaments. These toy models include vorticity diffusion via a white noise forcing of the inviscid equations, and thus extend inviscid models to include core dynamics and topology change (e.g., merger in two-dimensions and vortex reconnection in three dimensions). We demonstrate that although the $N=2$ two-dimensional model is qualitatively and quantitatively incorrect, it can be dramatically improved by accounting for self-advection. We then extend the two-dimensional SDE model to three dimensions using the semi-inviscid asymptotic approximation of Klein et al. ['Simplified equations for the interactions of nearly parallel vortex filaments,' *J. Fluid Mech.* 288, 201 (1995)] for nearly parallel vortices. This model is nonsingular and is shown to give qualitatively reasonable results until the approximation of nearly parallel vortices fails. We hope these simple toy models of vortex reconnection will eventually provide an alternative perspective on the essential physical processes involved in vortex merging and reconnection.

Kfoury, D. J.

"A ROUTINE METHOD FOR THE CALCULATION OF AERODYNAMIC LOADS ON A WING IN THE VICINITY OF INFINITE VORTICES"

TR-133-2, May 1966, MIT Aeroelastic and Structure Laboratory, Cambridge, MA

The vortex lattice method for the calculation of loads on a wing advancing in a uniform stream was extended to the case of a wing in the vicinity of infinite vortices. The results in the report were limited to checking the convergence of the calculations.

Khalil, S., Hourigan, K. and Thompson, M. C.

"RESPONSE OF UNCONFINED VORTEX BREAKDOWN TO AXIAL PULSING"

Physics of Fluids, Vol. 18, 2006, pp. 038102-1-038102-4

The response of unconfined swirling jets undergoing vortex breakdown to axial pulsing is explored experimentally. In particular, the combination of particle visualization and particle image velocimetry has enabled the effect of axial pulsing on the development of shear-layer flow structures and vortex breakdown to be quantified, as a function of both pulsing frequency and amplitude. A range of Reynolds and swirl numbers is considered. A key result is that application of low-level forcing at the natural frequency intensifies the shear-layer vortices considerably and results in a substantial relative downstream shift of the mean breakdown position.

Khan, F. A. and Mueller, T. J.

"VISUALIZATION OF TIP VORTEX/AIRFOIL INTERACTION"

Journal of Flow Visualization and Image Processing, Vol. 1, No. 1, 1993, pp. 35-41.

The effects of the vortical wake shed by a finite wing on a two-dimensional airfoil situated downstream were studied. Two forms of flow visualization were employed. First, the downstream airfoil boundary-layer behavior was studied using surface-film visualization. This consisted of smearing a mixture of propylene glycol and fluorescein onto the downstream airfoil, and viewing the resulting flow patterns under ultraviolet light. Second, the trajectory of the tip-vortex shed by the forward surface was examined using a kerosene vapor tracer. The freestream Reynolds number, based on the downstream airfoil chord length, was 150,000 for all tests. The surface-film visualization technique proved to be a very effective method for locating regions of separated flow on the airfoil. The smoke visualization provided good indication of the position of the tip-vortex relative to the two lifting surfaces. Several examples of both techniques are included in the paper.

Khoo, B. C., Yeo, K. S. and Lim, D. F.

"THE AXISYMMETRIC BOUNDARY LAYER BENEATH A RANKINE-LIKE VORTEX"

Experiments in Fluids, Vol. 22, 1997, pp. 300-311

An experimental investigation of the three-dimensional boundary layer induced by a Rankine-like vortex with its axis normal to a stationary disk is described. The velocity field through the boundary layer was measured for Reynolds number Re (based on the tangential velocity and radius at the disk edge) ranging from 10,000 to 25,000 at various radial distances by means of a 4-beam, 2-component Laser Doppler Anemometer. Our results show that the nature of the boundary layer is affected by two factors: a nonflexional instability caused by the crossflow velocity profile and a stability factor caused by the favorable pressure gradient. At lower Reynolds number, the radial pressure gradient has a very strong stabilizing effect on the boundary layer and acts to revert it to its laminar state upstream of the effusing core. At higher Re the nonflexional instability caused by the crossflow velocity dominates while the stabilizing influence of the favorable pressure gradient recedes. As such, laminar reversion likely occurs closer to the effusion core. Thus, the point of laminar reversion moves closer to the effusion core as the Reynolds number is increased.

Khoo, B. C., Yeo, K. S., Lim, D. F. and He, X.

"VORTEX BREAKDOWN IN AN UNCONFINED VORTICAL FLOW"

Experimental Thermal and Fluid Science, Vol. 14, 1997, pp. 131-148.

Flow visualization experiments were conducted on an unconfined vortex formed on a stationary impermeable base. At the low circulation range, all seven modes of vortex breakdown previously documented for a confined flow could be observed, despite the vast differences in the two sets of apparatus. The unconfined flow also revealed the existence of a conical breakdown. This occurrence has been recently observed under confined swirling flows. It is characterized by a conical breakdown envelope and occurs at the high swirl regions. At the higher circulation range, the vortex structure erupted from the base into a large-scale turbulent flow. Results are presented on a chart using parameters related to the intrinsic flow properties of the vortical flow -- circulation, extent of vortex stretching, and core size.

Khorrami, M. and Chang, C.-L.

"LINEAR AND NONLINEAR EVOLUTION OF DISTURBANCES IN SUPERSONIC STREAMWISE VORTICES"

AFOSR-TR-97, High Technology Corp., Hampton, VA, March 1997

Evolution of disturbances in a supersonic vortex is studied by using quasi-cylindrical linear stability analysis and parabolized stability equations (PSE) formulation. Appropriate mean-flow profiles suitable for stability analysis were identified and modeled successfully. Using the quasi-cylindrical linear-stability code, the stability characteristics of cylinder axisymmetric vortices were mapped thoroughly and discussed in detail. Important trends such as viscous and compressibility effects were obtained and analyzed. The results indicate that viscosity has very little effect while increasing Mach number

significantly stabilizes the disturbance. Nonlinear evolution of helical modes as well as modal interaction is also studied by using PSE. It is found that the growth of the disturbances results in the appearance of coherent large-scale motion and significant mean flow distortion in the axial velocity and temperature fields. In the end, nonlinear effects tend to stabilize the vortex.

Khorrami, M. R.

"STABILITY OF LONGITUDINAL VORTICES"

Potential Impacts of Advanced Aerodynamic Technology on Air Transportation System Productivity, edited by D. Bushnell, NASA TM-109154, NASA Langley Research Center, Hampton, VA, September 1994, pp. 94-95

Results of ongoing study on the stability of longitudinal vortices was given. The work was motivated by the need to destabilize and breakup the highly stable trailing line vortices generated by large commercial aircraft. Mean velocity components from a Batchelor vortex were used to perform a viscous linear stability analysis, from which two new viscous instability modes were identified, one axisymmetric and the other asymmetric. The results suggest that the key to controlling the break up and dissipation of trailing vortices was to induce at least a two-cell structure in them, and that the axisymmetric instability mode was the most likely to succeed. The desired velocity distribution might be achieved by using blowing or suction to alter the axial velocity component near the wing tip.

Khorrami, M. R.

"ON THE VISCOUS MODES OF INSTABILITY OF A TRAILING LINE VORTEX"

J. Fluid Mech., Vol. 225, April 1991, pp. 197-212

A viscous linear stability analysis of a trailing line (Batchelor) vortex is presented. Employing a staggered Chebyshev spectral collocation technique, very accurate results were obtained. The destabilizing role of viscous forces has been shown to produce two type of viscous instability modes. These viscous disturbances consist of an axisymmetric mode and an asymmetric mode. Comparison with experimental results and condensation trail observations are found to be in good qualitative agreement with the present study.

Khorrami, M. R. and Grosch, C.

"TEMPORAL STABILITY OF MULTIPLE CELL VORTICES"

AIAA Paper No. 1989-0987, Tempe, AZ, March 1989

The temporal stability of multiple cell vortices is considered. Employing a staggered Chebyshev spectral collection technique, the results are obtained very accurately and efficiently. It is shown that cell multiplicity in the vortex core has a drastic effect on the stability characteristics. While validating the spectral collocation algorithm, two new viscous modes of instability for Batchelor's vortex were

found. These two forms of instabilities include an axisymmetric, $n = 0$, as well as an asymmetric, $n = 1$, mode. Here n is the azimuthal wavenumber of the disturbance.

Khorrami, M. R. and Singer, B. A.

"STABILITY ANALYSIS FOR NOISE-SOURCE MODELING OF A PART-SPAN FLAP"

AIAA Journal, Vol. 37, No. 10, October 1999, pp. 1206-1212.

The relevant and important flow features of the local mean flowfield in the vicinity of a flap side edge are extracted from an extensive computational and experimental database. Based on the local flow features, possible mechanisms for flow-induced noise sources that are responsible for sound generation at flap side edges are conjectured. Relatively simple flow models for the dominant noise sources are proposed and developed. The models are based on the most amplified instability modes of the local shear flow. Stability analysis of the modeled flow field provides an estimate of the frequencies associated with the local flow unsteadiness. Computed frequencies show the proper trend and are in good agreement with NASA Langley Research Center's acoustic microphone array and unsteady surface-pressure measurements.

Khorrami, M. R., Choudhari, M. M., Cattafesta, III, L. N., and Won, C. C.

"ACTIVE CONTROL/ALLEVIATION OF TRAILING (STREAMWISE) VORTICES"

HTC-FR-1803, June 1995, High Technology Corporation, Hampton, VA

This research addressed the feasibility and development of an active control strategy to induce vortex decay in tip vortices. Destabilization and dissipation of wing tip vortices is the dominant issue for reducing wake hazard and increasing airport productivity. The wake hazard problem exists due to the longevity of trailing line vortices and their associated high rotational energy. The phase I investigation focused on an innovative technique for active excitation/energization of large-scale instability modes and inducement of bursting in tip vortices via localized external forcing. Our effort concentrated on modeling the vortex mean flow field, identifying and determining the frequencies and wavelengths of the instability waves, obtaining vortex receptivity to external forcing in the vortex initiation regime, and developing a single-frequency controller system to accomplish the external forcing. We have applied weakly nonlinear analysis to determine the mean flow modifications produced by an excited instability wave. The simulated distribution of the modified vortex circulation showed vortex disablement via bursting is readily achievable.

Khorrami, M. R., Singer, B. A. and Radeztsky, Jr., R. H.

"REYNOLDS-AVERAGED NAVIER-STOKES COMPUTATIONS OF A FLAP-SIDE-EDGE FLOWFIELD"

AIAA Journal, Vol. 37, No. 1, January 1999, pp. 14-22

An extensive computational investigation of a generic high-lift configuration comprising a wing and a half-span flap reveals details of the mean flow field for flap deflections of 29 and 39 deg. The computational effort involves solutions of the thin-layer form of the Reynolds-averaged Navier-Stokes equations. For both flap deflections, the steady results show the presence of a dual-vortex system: a strong vortex forming on the lower portion of the flap side edge and a weaker one forming near the edge on the flap top surface. Downstream, the vortex on the flap side edge grows and eventually merges with the vortex on the flap top surface. Comparison of on- and off-surface flow quantities with our previous experimental measurements shows remarkable agreement. For the 39-deg flap deflection, the calculation also reveals the occurrence of a vortex breakdown, which is corroborated by five-hole probe velocity measurements performed in the Quiet Flow Facility at NASA Langley Research Center. The presence of the vortex breakdown significantly alters the flow field near the side edge.

Khosravi, M., Sarkar, P. and Hu, H.

"AN EXPERIMENTAL INVESTIGATION ON THE NEAR WAKE CHARACTERISTICS OF A DARRIOUS VERTICAL-AXIS WIND TURBINE"

AIAA Paper 2016-1732, January 2016, San Diego, CA.

The wake flow field ($x/D < 2.5$) measurements behind a two-bladed Darrious type VAWT were carried out by using a high-resolution PIV system, and the results obtained at two different horizontal (x - y) planes, at the equator height ($H/2$) and above the equator height ($3H/4$), for four different tip speed ratios (2, 2.5, 3 and 3.5) of the VAWT were then evaluated and compared. The wake of the VAWT is found to be significantly different to that of the HAWT's. At lower tip-speed-ratio (i.e. TSR 2) the wake tends to be very asymmetric and skewed with relatively higher amount of momentum in the wake in comparison to higher tip-speed ratios (i.e. 3 or 3.5). As tip-speed ratio increases, there is a tendency in flow stagnation in the wake and eventually flow reversal would occur at higher tip-speed-ratios. The wake dynamics (i.e., the instabilities inherent in VAWT) behind the VAWTs would lead to a much faster wake recovery in comparison to the HAWTs.

Khosravi, S. and Zingg, D. W.

"AEROSTRUCTURAL PERSPECTIVE ON WINGLETS"

Journal of Aircraft, Vol. 54, No. 3, May-June 2017, pp. 1121-1138.

This paper presents an aero-structural perspective on the potential benefits of wings with winglets in comparison to planar wings of the same projected span. There is no consensus in the current literature on the efficiency gains possible from winglets. The present paper takes a step further toward understanding the tradeoffs in the design of wings with winglets using high-fidelity numerical optimization based on both purely aerodynamic and fully coupled aero-structural analysis. The high-fidelity analysis in both cases uses the Euler equations to model the flow along with a friction drag estimate based on the surface area. Three configurations are considered: winglet-up, winglet-down, and planar. The results show that downward winglets produce a greater drag reduction than upward

winglets for two reasons. First, the downward winglet moves the tip vortex further away from the wing from a purely aerodynamic standpoint. Second, the winglet-down configuration has a higher projected span at the deflected state due to the structural deflections. This indicates that fully coupled high-fidelity aero-structural optimization is required to quantify the benefits of winglets properly. The winglet-down configuration can reduce the total drag by up to 2 percent at the same weight as the optimal planar counterpart.

Khou, J.-C., Ghedhaifi, W., Vancassel, X. and Garnier, F.

"SPATIAL SIMULATION OF CONTRAIL FORMATION IN NEAR-FIELD OF COMMERCIAL AIRCRAFT"

Journal of Aircraft, Vol. 52, No. 6, November-December 2015, pp. 1927-1938.

During this study, three-dimensional numerical simulations of contrails generated by commercial aircraft in cruise conditions were performed. The objective was to study the early development of contrails in the near field of an aircraft, including engine core and bypass flows. Computational fluid dynamics simulations, based on the three-dimensional Reynolds-averaged Navier-Stokes approach, were carried out on a realistic aircraft geometry. A microphysical model was implemented in the computational fluid dynamics code to simulate particle growth using a Eulerian approach. Results showed that the mixing process in the bulk plume were in good agreement with the literature. Then, the early growth of a contrail in the near wake of the aircraft was investigated for two ambient relative-humidity conditions. This parameter played a significant role in contrail local properties. Increased relative humidity led to an increase in the fraction of particles under the supersaturated condition and condensation rate. This resulted in a higher mean particle radius and, consequently, in a higher optical depth, making contrails more distinct. Particle-size distribution shifted toward larger particles due to an increase in available vapor and got narrower as the relative humidity increased because more particles were in favorable conditions for ice growing.

Kiang, R. L.

"SUB-SCALE MODELING OF AIRCRAFT TRAILING VORTICES"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 81-95

A pilot study of trailing vortices using a sub-scale model is described. The essential feature of the laboratory facility is to have a vortex-generating wing moving along a pair of elevated rails so that the vortices shed by the wing remain relatively fixed with respect to ground-based instrumentation and can be observed and measured throughout their entire life-span. The vortices are rendered visible by smoke traces and by drifting soap bubbles. Hot-wire anemometer probes are used to study the turbulence nature of the vortices. Geometrically similar wings of different sizes running at various speeds and angles of attack have been tested. A scaling study is also described based on existing theories that predict the decay rate of a turbulent line vortex. None of the theories examined is capable of correlating the results of the sub-scale experiments.

Kicinger, R., Chen, J.-T., Steiner, M. and Pinto, J.

"AIRPORT CAPACITY PREDICTION WITH EXPLICIT CONSIDERATION OF WEATHER FORECAST UNCERTAINTY"

Journal of Air Transportation, Vol. 24, No. 1, January 2016, pp. 18-28.

This paper describes a stochastic analytical model for predicting airport capacity with a look-ahead horizon suitable for strategic traffic flow management. The model extends previous research on airport capacity estimation by explicitly integrating the impact of terminal weather and its uncertainty. Different types of weather forecast inputs are explored, including deterministic forecasts, deterministic forecasts with forecast error models, and ensemble forecasts, to produce distributions of predicted arrival and departure capacity for each runway configuration at an airport. The paper introduces a mathematical capacity prediction model and weather data sources supported by a proof-of-concept prototype implementation, including results of validation studies at Hartsfield-Jackson Atlanta International Airport. These results are compared with standard airport benchmark capacities and actual observed throughputs. Results show that our analytical airport capacity model accurately predicts maximum available airport capacity for Hartsfield-Jackson Atlanta International Airport for different weather conditions. The validation studies reveal a limited impact of forecast uncertainty representation on the accuracy of airport capacity predictions.

Kida, S.

"DESCRIPTION AND DYNAMICS OF VORTICAL STRUCTURES OF TURBULENCE"

Lecture Notes in Physics, Vol. 567, 2001, pp. 3-16

The vortical structure of turbulence is analyzed in terms of the low-pressure vortex, the central axis of which is given by loci of pressure minimum and the core is defined as concave regions of pressure. Since the position and direction of vortex axes are specified, we can analyze the vorticity field by decomposing the axial and cross-axial components. It is found that the fundamental vortical structure - the elementary vortex - is a tubular vortex core with strong axial vorticity accompanied with spirally wrapped vortex layer of cross-axial vorticity. These surrounding layers can contribute more than the tubular cores to energy dissipation because of their wider spatial extent.

Kida, S. and Miura, H.

"IDENTIFICATION AND ANALYSIS OF VORTICAL STRUCTURES"

European Journal of Mechanics, B/Fluids, Vol. 17, No. 4, 1998, pp. 471-488.

Various identification and visualization methods of vortical structures, especially of slender vortices, are critically reviewed with a special attention to their objectivity. The sectional-swirl-and-pressure-minimum scheme is presented as a new identification method and applied to homogeneous turbulence. Since the physical quantities associated with an individual vortex can be analyzed separately, this new scheme enables us to investigate quantitatively various physical characteristics

related to vortices, such as the variations of the core shape, the circulation and the vorticity vector along a vortex and the temporal evolution of arbitrarily selected vortices.

Kida, S. and Takaoka, M.

"VORTEX RECONNECTION"

Annual Review Fluid Mechanics, 1994, Vol. 26, pp. 169-189

Understanding the dynamics and the mutual interaction among various types of vortical motions, including vortex reconnection, is a key ingredient in clarifying and controlling fluid motions. Thanks to the rapid development of supercomputers, the direct numerical study of vortex reconnection has become possible in the past few years. Complete data of field quantities, such as velocity, vorticity, and concentration of a passive scalar, at any time and at any position can be stored in the computer memory. There have been many numerical simulations published so far with various motivations ranging from fundamental physics to engineering application. But for understanding the fundamental mechanism of vortex interaction, which is our main concern here, it is better to investigate the simplest situation possible that still retains some essential mechanism. In this review we describe the current understanding of vortex (vorticity or scalar) reconnection and the related phenomena from a fundamental point of view.

Kida, S., Kawahara, G., Tanaka, M. and Yanase, S.

"VORTICITY DYNAMICS AROUND A STRAIGHT VORTEX TUBE IN A SIMPLE SHEAR FLOW"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany, pp. 173-182.

The mechanism of wrap, tilt and stretch of vorticity lines around a strong thin straight tubular vortex in a simple shear flow is investigated analytically. An asymptotic expression of the vorticity field around a vortex which starts with a filament is derived at large vortex Reynolds numbers and at short times of evolution. An oblique vortex, which inclines from the streamwise direction both to the vertical and the spanwise, wraps and stretches the simple shear vorticity to form double spiral layers of high azimuthal vorticity of alternating sign in adjacent spirals. These spirals induce axial shear flows of the same spiral shape and sign which in turn tilt the simple shear vorticity toward the axial direction. Vorticity lines wind helically around the vortex, which results in conversion of the simple shear vorticity to the axial direction. The effects of system rotation on this interaction are also discussed.

Kidd, R. M.

"WAKE TURBULENCE - THE INVISIBLE KILLER"

CATCA Journal, Vol. 5, Fall 1973, pp. 4-7

A number of hazardous takeoff situations and some accidents caused by wake vortices (wing tip vortices) from a preceding aircraft on a congested runway are described. Details are given on a wake vortex accident of June 8, 1966, resulting in a collision of an XB-70 and an F-104 over the Mojave Desert in California, and on the crash of a DC-9 behind a DC-10 at Fort Worth on May 30, 1972. Recommendations made by the ALPA air safety team after the crash are listed.

Kier, T. M.

"AN INTEGRATED LOADS ANALYSIS MODEL FOR WAKE VORTEX ENCOUNTERS"

International Forum on Aeroelasticity and Structural Dynamics (IFASD 2013), Paper 30C, June 2013, Bristol, UK.

When a plane crosses the wake generated by a preceding aircraft, large dynamical loads in the order of the design loads may be induced. Loads analysis models for such wake vortex encounters need to consider aspects important for maneuver, as well as gust type responses. If the angle between the path and the trailing vortices is small, the encounter is maneuver like due to large induced roll motion. When the vortices are crossed almost perpendicularly, a gust type response is to be expected, where unsteady aerodynamic effects are significant. Previously a modeling approach of an integrated loads analysis model suitable for wake vortex encounters was presented. This contribution will further investigate the requirements for such flight loads models for wake vortex encounters. One important aspect is, that the bandwidth of the excitation due to gust type wake vortex encounters is considerably larger compared to classical design gusts. Hence, the convergence behavior for high reduced frequencies of the doublet lattice models needs to be examined in more detail. A rational function approximation (REA) is required to make the unsteady aerodynamics amendable for nonlinear time domain simulations. Previously, a 'physical' RFA could significantly improve the results for incompressible flow at high reduced frequencies by explicit approximation of the added mass term. The 'physical' RFA scheme is now extended to the compressible regime. The results are compared to the solution of the Poisson's equation and a velocity potential method for unsteady motion of airfoils in compressible flow. Further, the (time domain) integral loads analysis model is compared to a frequency domain approach. Induced velocities due to a pre-described trajectory for a wake crossing are determined. A subsequent Fourier transformation yields the excitation spectrum for the frequency domain calculations. Various encounter angles with wake vortices are computed and compared to time domain simulations, where the trajectory is determined as a nonlinear response during the simulation. Results show that in some encounter scenarios these nonlinearities can become crucial.

Kikumoto, H., Ooka, R., Sugawara, H. and Lim, J.

"OBSERVATIONAL STUDY OF POWER-LAW APPROXIMATION OF WIND PROFILES WITHIN AN URBAN BOUNDARY LAYER FOR VARIOUS WIND CONDITIONS"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 164, 2017, pp. 13-21.

This paper investigates the accuracy and limitations of wind profile modeling using the power-law (PL), especially for low-speed conditions in which air and thermal pollution can prevail. A Doppler lidar system and ultrasonic anemometer were installed to measure wind profiles and turbulence statistics in the urban boundary layer of Tokyo, Japan over seven months. The wind speeds at a height of 67.5 m (u) at average intervals of 10 min were < 6 m/s for 80 percent of the observation period. For low wind speeds, the difference in wind direction with height is significant, making it difficult to determine the prevailing wind direction. The PL could be used to model the wind profiles for high wind speeds ($u > 6$ m/s), whereby the power-law index (PLI) converges to 0.25. Although the PL model can be used for an ensemble-averaged profile composed of all profiles from the observed period, the accuracy of the PL decreases for profiles with low speeds and short average time intervals. The PLI on average decreases to -0.21 for low wind speeds and shows diurnal changes with small PLIs during the daytime. This research quantitatively discusses the application limits of the PL for wind profiles under low-speed conditions.

Kim, D., Kim, T., Oh, G., Huh, J. and Ko, K.

"A COMPARISON OF GROUND-BASED LIDAR AND MET MAST WIND MEASUREMENTS FOR WIND RESOURCE ASSESSMENT OVER VARIOUS TERRAIN CONDITIONS"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 158, 2016, pp. 109-121.

In order to assess reliability of measurements from LiDAR (Light Detection and Ranging), a measurement campaign was led using ground-based LiDAR of WINDCUBE V2 and meteorological masts at three measurement sites: Sumang, Gangjeong, and Susan, on Jeju Island, Korea. Each site had a different topographical complexity, which was evaluated by using a Ruggedness Index (RIX). Wind data was collected for 11-14 days from four heights on each site's met mast. Data filtering was done to ensure data comparability between LiDAR and wind sensors. Analyses of LiDAR error, standard deviation, turbulence intensity and LiDAR error rate were conducted on data coming from each site. Also, the CFD analysis was performed at Sumang with the highest RIX. As a result, the concurrent wind measurement slopes were all close to one based on linear regression analysis. The coefficient of determination was almost all more than 0.9 for all heights at each site. LiDAR error rates for the measurement sites ranged from approximately between 2% and 6%. The result of the CFD analysis showed that the depression was formed between two parasitic cones, between which the measurement point of Sumang was located, which led to greater positive LiDAR error.

Kim, H., Williams, M. H. and Lyrantzis, A. S.

"IMPROVED METHOD FOR ROTOR WAKE CAPTURING"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 794-803

An accurate simulation of rotor aerodynamics has been a challenging problem for the computational fluid dynamics community, largely because numerical diffusion in the typically coarse grids away from the blades seriously degrades the prediction of the returning wakes. A numerical scheme is proposed

to improve the reconstruction stage of a MUSCL approach in the framework of a finite volume formulation. A fourth-order upwind scheme, based on the interpolation of the local characteristic variables in the reconstruction stage, is applied instead of the conventional third-order upwind-biased scheme. Different slope limiters are applied to different characteristic fields to reduce the numerical dissipation of entropy and shear waves. We have implemented the proposed scheme into the TURNS code. Numerical results for a hover case show a significant improvement in the wake capturing capability over the baseline TURNS code.

Kim, H., Williams, M. H. and Lyrintzis, A. S.

"AN IMPROVED METHOD FOR ROTOR WAKE CAPTURING"

AIAA Paper No. 2001-2669, Anaheim, CA, June 2001

Accurate simulation of rotor aerodynamics has been a challenging problem for the computational fluid dynamics (CFD) community, largely because numerical diffusion in the typically coarse grids away from the blades seriously degrades the prediction of the returning wakes. In this paper, we propose a numerical scheme to improve the reconstruction stage of a MUSCL (Monotone Upstream-centered Scheme for Conservation Law) finite volume formulation. A fourth-order upwind scheme, based on the interpolation of the local characteristic variables in the reconstruction stage is applied instead of the conventional third-order upwind biased scheme. Different slope limiters are applied to different characteristic fields to reduce the numerical dissipation of entropy and shear waves. We have implemented the proposed scheme into the TURNS (Transonic Unsteady Rotor Navier-Stokes) code. Numerical results for a hover case show a significant improvement in the wake capturing capability over the baseline TURNS code.

Kim, H.-J., Lee, S. and Fujisawa, N.

"COMPUTATION OF UNSTEADY FLOW AND AERODYNAMIC NOISE OF NACA0018 AIRFOIL USING LARGE-EDDY SIMULATION"

International Journal of Heat and Fluid Flow, B/Fluids, Vol. 27, Issue 2, April 2006, pp. 229-242

The flow field around a symmetrical NACA airfoil in the uniform flow under generation of noise was numerically studied. The numerical simulation was carried out by a large-eddy simulation that employs a deductive dynamic model as the sub-grid scale model. The results at small angle of attack indicate that the discrete frequency noise is generated when the separated laminar flow reattaches near the trailing edge of pressure side and the strong instability thereafter affects positive vortices shed near the trailing edge. The quasi-periodic behavior of negative vortex formation on the suction side is affected by the strength and the periodicity of positive vortices near the trailing edge. The computation using aero-acoustic analogy indicates the primary discrete peak at the Strouhal frequency by the vortex shedding from the trailing edge, which is in a close agreement with the experiment.

Kim, J. M. and Komerath, N. M.

"SUMMARY OF THE INTERACTION OF A ROTOR WAKE WITH A CIRCULAR CYLINDER"

AIAA Journal, Vol. 33, No. 3, March 1995, pp. 470-478.

To compute the aerodynamics of a rotorcraft in low-speed flight, the interaction of the strong vortices in the rotor wake with the airframe must be modeled. Using a hemisphere cylinder airframe and a 2-bladed rotor for reference, the various phenomena encountered during such interactions are summarized, combining previous results on various configurations with recent experimental results. Differences between the interaction at the front and aft positions of the wake are discussed. The pre-collision phase conforms to expectations from potential flow, and includes distortion of the vortex trajectory determined by the sense of rotation of the vortex. The collision phase involves complex boundary layer interactions. The axial velocity in the vortex core causes substantial asymmetry, and influences the surface pressure distribution on the airframe side under the advancing rotor blade, where the axial flow stagnates. The post-interaction vortex is much weaker, but still contains some swirl energy. Where flow separation occurs due to airframe shapes, the interaction is not modified significantly, because the vortex dominates the interaction with separated shear layers for parameter values of practical interest. Areas of remaining uncertainty are discussed.

Kim, J.-H., Chan, W. N. and Sridhar, B.

"APPLICATION OF AVIATION TURBULENCE INFORMATION TO AIR-TRAFFIC MANAGEMENT (ATM)"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 24, 2016, Springer International Publishing Switzerland, pp. 481-500.

Unexpected turbulence, especially in the upper troposphere and lower stratosphere where cabin crews and passengers in cruising aircraft are likely to be unbuckled, causes in-flight injuries, structural damage, and flight delays. Therefore, turbulence information can be used to improve safety while pursuing efficiency in the air-traffic management (ATM). In this chapter, an optimal flight path that minimizes both total flight time (e.g., fuel consumption) and potential encounters of turbulence from departure to arrival airports is derived by combining simple modeling of aircraft flight trajectories with wind and turbulence predictions. In addition, probabilistic ensemble turbulence forecasts, evaluated against in situ eddy dissipation rate turbulence observations from commercial aircraft, are applied to suggest an optimal strategic and tactical ATM route planning for given weather and turbulence conditions in the USA. The variations of long-haul transoceanic flight routes and their turbulence potentials are also investigated using global reanalysis data to understand how the upper-level large-scale flow patterns can affect the long-term ATM planning through the changes of winds and turbulence conditions.

Kim, J.-H., Yoo, J. Y. and Kong, S.-H.

"DILATATION AND VORTEX STRETCHING EFFECTS ON TURBULENCE IN ONE-DIMENSIONAL/AXISYMMETRIC FLOW"

AIAA Journal, Vol. 40, No. 12, December 2002, pp. 2476-2482.

A theoretical analysis is carried out to predict the amplification of turbulence in flows experiencing one-dimensional and axisymmetric dilatations. When three representative vortices are tracked, the variations of vortex radius and vorticity are calculated, and then the amplification of turbulence is obtained from them. When a vortex is tracked, conservation laws of mass and angular momentum of the vortex are used. For a one dimensionally compressed flow, the present analysis slightly underestimates the amplification of velocity fluctuations and turbulent kinetic energy, relative to that of rapid distortion theory in the solenoidal limit. For an axisymmetrically distorted flow, the amplification of velocity fluctuations and turbulent kinetic energy and the anisotropy depend not only on the density ratio, but also on the ratio of streamwise mean velocities, which represents streamwise vortex contraction/stretching. The amplification predicted by the present analysis is in excellent agreement with that by the rapid distortion theory. In both flows, the amplification of turbulence is dictated by the mean density ratio, whereas the anisotropy is primarily dictated by the flow boundary. However, streamwise vortex stretching/contraction alters the amplification slightly and the anisotropy significantly in the axisymmetric flow.

Kim, M. J. and Mook, D. T.

"APPLICATION OF CONTINUOUS VORTICITY PANELS TO GENERAL UNSTEADY INCOMPRESSIBLE TWO-DIMENSIONAL LIFTING FLOWS"

J. Aircraft, Vol. 23, No. 6, June 1986, pp. 464-471

Continuous vorticity panels are used to model general unsteady inviscid, incompressible, two-dimensional lifting flows. The geometry of the airfoil is approximated by a series of short straight segments having endpoints that lie on the actual surface. A piecewise linear, continuous distribution of vorticity over the approximated surface is used to generate the disturbance flow. The no-penetration condition is imposed at the midpoint of each segment and at discrete times. The wake is simulated by a system of discrete vortex cores (point vortices), which move at the local particle velocity. At each time step a new core is placed at the trailing edge, and the condition of constant circulation around wing and wake is imposed. Because the system is overdetermined, an optimization scheme is used to obtain simultaneously the unknown values of the surface velocity at the endpoints of the segments and the unknown value of the circulation around the core at the trailing edge. Comparisons are made with known exact solutions and wind tunnel data for one- and two-component airfoils in steady flow, and with other computed results and one experiment for unsteady flow. The present approach provides an attractive alternative to those developed earlier, being easy to formulate, easy to use, and very accurate.

Kim, S.-C., Lee, J.-Y. and Sohn, S.-I.

"LONG TIME COMPUTATION OF TWO-DIMENSIONAL VORTEX SHEET BY POINT VORTEX METHOD"

Journal of the Physical Society of Japan, Vol. 72, No. 8, August 2003, pp. 1968-1976.

Two-dimensional vortex sheet suffers an unstable deformation from the Kelvin-Helmholtz instability and a curvature singularity which develops in a finite time. In this paper, long time computations of the two-dimensional vortex sheet are performed by a robust and efficient numerical method with high accuracy. To handle the rapid and non-uniform stretching of the interface, we adopt the adaptive point insertion and redistribution procedures. Computational results show highly refined structures of a complex and chaotic pattern for the vortex sheet up to very long time.

Kim, S.-E. and Rhee, S. H.

"PREDICTION OF TIP-VORTEX FLOW PAST A FINITE WING"

AIAA Paper No. 2005-0058, Reno, NV, January 2005

Turbulent flow past a finite wing is computed to assess the fidelity of modern computational fluid dynamics (CFD) in predicting the tip-vortex flow. Efficacy of a feature-adaptive local mesh adaption is demonstrated to resolve the steep gradients in the flow-field near the tip-vortex. The impact of turbulence modeling is evaluated using several popular eddy-viscosity models and a Reynolds-stress transport model. The results indicate that the combination of a computational mesh with adequate resolution, high-order spatial discretization scheme and advanced turbulence models can predict the tip-vortex flow with commendable accuracy.

Kim, Y. and Park, S. O.

"WINGTIP VORTEX SIMULATION BY USING NONEQUILIBRIUM EDDY VISCOSITY MODEL"

Journal of Aircraft, ol. 47, No. 6, Nov.-Dec. 2010, pp. 2184-2187.

This study investigates the performance of the nonequilibrium eddy viscosity model, proposed by Yoshizawa et al., for the simulation of the wingtip vortex. Results predicted by using the standard k-e model, the two-component-limit (TCL) second-moment closure model, and the nonequilibrium model were compared with the experimental data of Chow et al. Through the comparison, we found that the nonequilibrium model performed as good as or only slightly inferior to the TCL model. We thus conclude that the nonequilibrium eddy viscosity model is indeed a very good model for practical wingtip vortex simulation, considering the fact that the TCL model is a Reynolds stress transport model, which is not as easy as two-equation turbulence models for practical application.

Kimura, Y.

"MOTION OF THREE-DIMENSIONAL VORTEX FILAMENT AND PARTICLE TRANSPORT"

In IUTAM Symposium on Elementary Vortices and Coherent Structures: Significance in Turbulence Dynamics, edited by S. Kida, Springer, The Netherlands, 2006, pp. 275-282.

Motions of fluid particles advected by a 3D vortex filament are studied. As extensions of a circular vortex ring, which provides a basis of fluid transport by vortex, two types of motions, elliptic vortex ring

and vortex soliton are considered. For an elliptic vortex ring, it is verified that the local induction equation (LIE) describes its motion properly if the aspect ratio is close to 1. Using the solution of LIE, particle motions are simulated for two different induction constants corresponding to a thin and a fat vortex for the circular vortex ring case, respectively. Intrinsic difficulty for calculating the finite transported volume by an elliptic vortex ring is suggested. For a vortex soliton, it is demonstrated that particle motions are confined in a torus near the kink of a soliton for a wide range of parameters that characterize the shape and the strength of the vortex soliton.

Kimura, Y., Zawadzki, I. and Aref, H.

"VORTEX MOTION, SOUND RADIATION, AND COMPLEX TIME SINGULARITIES"

Physics of Fluids, Vol.A2, No. 2, Feb. 2009, pp. 214-219.

The equations of motion for interacting point vortices can be embedded in a system of ordinary differential equations with polynomial couplings and thus subjected to the 'Painleve test' for integrability. The arrays of singularities produced by this analysis confirm well known results on integrability and chaos in few-vortex systems, and are shown by further numerical experiments to predict qualitative features of the low Mach number sound radiation from the vortex system. The correspondence between singularity distribution, vortex trajectory pattern, time series of far-field pressure, and sound spectrum are illustrated and discussed based on a parametric numerical survey of some simple three- and four-vector motions. The results suggest a physical interpretation of the Painleve singularities.

Kindler, K., Goldhahn, E., Leopold, F. and Raffel, M.

"RECENT DEVELOPMENTS IN BACKGROUND ORIENTED SCHLIEREN METHODS FOR ROTOR BLADE TIP VORTEX MEASUREMENTS"

13th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, June 2006

Compressible blade tip vortices (BTV) of rotary wings have been subject of numerous investigations and their importance for the understanding of the helicopter flow field has clearly been drawn. Due to its great impact on the dynamics of the flow field, the investigation of the BTV is directly linked to issues of flow control and aeroacoustic optimization. However, despite of the velocity field data of the BTV, additional density information for vortex modeling is desirable. In this work we briefly describe the set-up of an airborne background oriented optical stereoscopic schlieren (BOSS) system for helicopter flight tests as well as preliminary experimental results of background oriented optical tomography (BOOT) of a 0.4 Mach scaled rotor model investigation. The tomographic approach enabled us computing an estimate of the tip vortex density field. This method is demonstrated to yield reasonable scales of the vortex core diameter. The advantages and applicability of the filtered back-projection method for rotor investigations will be discussed.

Kindler, K., Goldhahn, E., Leopold, F. and Raffel, M.

"RECENT DEVELOPMENTS IN BACKGROUND ORIENTED SCHLIEREN METHODS FOR ROTOR BLADE TIP VORTEX MEASUREMENTS"

Experiments in Fluids, Vol. 43, 2007, pp. 233-240

The compressible blade tip vortex of rotary wings has been the subject of numerous investigations and its importance for the understanding of the helicopter flow field has been clearly emphasized. Due to its great impact on the dynamics of the flow field, the investigation of the tip vortex is directly linked to issues of flow control and aero-acoustic optimization. However, among velocity field data, additional core density information on the blade tip vortex is desirable with a view to vortex modelling. In this work we describe an airborne background oriented Schlieren system for full-scale helicopter flight tests as well as the first results of the tomographic reconstruction of the compressible vortex core. We report the measurements of both a 0.4 Mach-scaled rotor model of the MBB BO 105 and the corresponding full-scale helicopter in hover flight condition. The tomographic reconstruction of the data allows us to estimate the density and the radius for the viscous core.

Kindler, K., Mulleners, K. and Raffel, M.

"TOWARDS IN-FLIGHT MEASUREMENTS OF HELICOPTER BLADE TIP VORTICES"

Advanced In-Flight Measurement Techniques, Research Topics in Aerospace, edited by F. Boden et al, 2013, Springer-Verlag Berlin Heidelberg, pp. 171-185.

In the framework of the AIM project the near field of the blade tip vortex of a full-scale helicopter in simulated hover flight was investigated by combining three-component Particle Image Velocimetry and Background Oriented Schlieren measurements. The velocity field measurements in the range of wake ages of 1 degree to 30 degrees in azimuth provided a reference for a quantitative analysis of the Schlieren results yielding vortex core density estimates. Ongoing vortex roll-up was observed at 1 degree while considerable aperiodicity was persistent thereafter. The vortex parameters for greater than 1 degree were consistent with the Scully vortex model. However, the challenges of full-scale, outdoor testing, especially the limited spatial resolution and aperiodicity effects, yielded a higher level of measurement uncertainty as compared to sub-scale experiments.

Kindler, K., Mulleners, K., Richard, H., van der Wall, B. G. and Raffel, M.

"APERIODICITY IN THE NEAR FIELD OF FULL-SCALE ROTOR BLADE TIP VORTICES"

Experimental Fluids, Vol. 50, 2011, pp. 1601-1610.

Blade tip vortices are the dominant vortical structures of the helicopter flow field. The inherent complexity of the vortex dynamics has led to an increasing interest in full-scale in situ experiments, where the near field, closely behind the blade, is of particular interest, since measures of vortex control mostly target this initial stage of development. To examine the near field, three-component particle image velocimetry (PIV) measurements of blade tip vortices of a full-scale helicopter in simulated hover

flight in ground effect were conducted. A feasible and robust evaluation procedure was developed to minimize the shortcomings of full-scale PIV applications, such as a moderate spatial resolution and an elevated measurement noise level. At vortex ages ranging from rotor azimuth 1 to 30 degrees, a pronounced aperiodicity and asymmetry of the vortex were observed in sections perpendicular to the vortex axes. At a rotor azimuth of 1 degree, a preferential orientation of the vortex was observed. For increasing wake age, vortex wandering increased while the asymmetry of the vortex cores decreased. The high level of aperiodicity and core asymmetry must be taken into account when considering phase-averaged vortex characteristics in the near wake region.

King, R. M. and Gopalaranthnam, A.

"IDEAL AERODYNAMICS OF GROUND EFFECT AND FORMATION FLIGHT"

J. of Aircraft, Vol. 42, No. 5, September-October 2005, pp. 1188-1199

The theoretical induced-drag benefits are presented for ideally loaded wings flying in formation and ground effect. An optimum-downwash approach using a vortex-lattice implementation was used to study formations of wings loaded optimally for minimum induced drag with roll trim. An exact approach was also developed to examine the drag of elliptically loaded wings in formation. The exact approach allows for decomposition of the benefits by considering the mutual-interference contributions from different pairs of wings in a formation. The results show that elliptically loaded wing formations have nearly the same drag as optimally loaded wing formations. For a formation of planar wings, in or out of ground effect, the optimum lateral separation corresponds to a 10% span overlap of wing tips. At this optimum lateral separation, a formation of 25 elliptically loaded wings flying out of ground effect experiences an 81% drag reduction compared to 25 wings flying in isolation. For large formations, in or out of ground effect, multiple local optima are seen for the lateral separation. Large formations experience small additional benefits caused by ground effect even at relatively large ground clearances of four wing spans. The shape of vee formations, for equipartition of drag benefits, is found to be nearly independent of flight in or out of ground effect.

Kini, S. and Conlisk, A. T.

"NATURE OF LOCALLY STEADY ROTOR WAKES"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 750-758

The regions over which steady and unsteady rotor wake patterns exist have been examined numerically for one- and two-bladed rotors. A lifting-line theory is used to model each rotor blade, and a time-stepping vortex method is used to calculate the tip-vortex motion. Tip-vortex geometries for a rotor in hover and vertical climb have been computed. The velocities within the first few turns of the wake have been obtained, and the results indicate a periodic nature of the wake in both time and space. Temporal aperiodicity is observed beyond the first few turns of the tip vortex for hovering rotors, whereas for rotors in sufficient climb the entire wake is steady relative to the blades and both spatially and temporally periodic. Both Euler and Adams-Moulton schemes have been tested for

accuracy. The numerical results are shown to be independent of both time step and spatial grid below clearly defined values. Rotor thrust calculations have been performed and the effect of the lower wake on rotor thrust determined. The computed thrust values show some variation because the lower wake remains unsteady. The results for the wake geometry are analyzed and compared to previous predictions and two distinct sets of experimental results.

Kini, S., Godavarty, V. and Conlisk, A. T.

"COMPARISON OF TWO DISTINCT MODELS OF ROTOR WAKES WITH EXPERIMENT"

AIAA Paper No. 2002-0158, Reno, NV, January 2002

Rotor blades are often modeled using either the lifting-line or the lifting-surface approach. Classical lifting-line theory treats the case of a high aspect ratio blade where the blade is modeled by a single bound vortex line. The lifting-line approach will thus be expected to be accurate for large aspect ratio wings and rotor blades. In the lifting-surface approach the blade is modeled by a thin lifting surface to more realistically resolve the chordwise flow close to the blade surface and its effect on the formation of the tip-vortex and consequently the entire wake. The objective of the present work is to compare results from two distinct vortex-wake models. The Wake Model with Lifting-Line has a robust model for the wake. The Lifting-Surface Model with Wake Effects has a robust model for the lifting-surface with additional terms in the governing equations representing a simplified model for the wake. Bound and tip-vortex strengths, tip-vortex trajectories, and velocity profiles very close to the blade are evaluated using these models. It is observed that the results obtained from these models are comparable. To establish the validity of the models the results are also compared with experimental data.

Kirkman, K. L., Brown, C. E. and Goodman, A.

"EVALUATION OF EFFECTIVENESS OF VARIOUS DEVICES FOR ATTENUATION OF TRAILING VORTICES BASED ON MODEL TESTS IN A LARGE TOWING BASIN"

NASA CP-2202, December 1973, Hydronautics Inc., Laurel, MD

The effectiveness of various candidate aircraft-wing devices for attenuation of trailing vortices generated by large aircraft is evaluated on basis of results of tests conducted with a 0.03-scale model of a Boeing 747 transport aircraft using a unique technique developed at the Hydronautics Ship Model Basin. Emphasis is on the effects produced by these devices in the far field where the unaltered vortex wakes could still be hazardous to small following aircraft.

Kirkpatrick, D. L. I.

"EXPERIMENTAL INVESTIGATION OF THE BREAKDOWN OF A VORTEX IN A TUBE"

ARC Paper CP-821, 1965, Royal Aircraft Establishment, Bedford, England

The distribution of the total pressure and the angle of swirl across a vortex in a tube were measured using a pitot probe upstream of breakdown. The static pressure distribution along the length of the tube containing the breakdown was also measured. It was found that the total pressure fell sharply in the vortex core towards a very low value on the axis, and that the swirl-angle distribution was similar to that of an exponential vortex. The static pressure distribution along the wall of the tube was found to include a positive pressure gradient upstream and a negative pressure gradient downstream of the breakdown's position. When breakdown did not occur these pressure gradients were not present. From the total pressure and swirl-angle distributions across the vortex, the static and dynamic pressure distributions and the axial and circumferential velocity distributions were calculated. These results will be used as boundary conditions for numerical solution of the equations of motion of the vortex.

Kirschbaum, H. W.

"ESTIMATION OF MOMENTS OF INERTIA OF AIRPLANES FROM DESIGN DATA"

NACA TN-575, July 1936, Langley Aeronautical Lab., Langley Field, VA.

A method of determining the moments of inertia of an airplane from design data pertaining to the weights and locations of the component parts is described. The computations required to ascertain the center-of-gravity position are incorporated with the calculations of moments of inertia. A complete set of data and calculations for a modern airplane is given to illustrate the procedure. From a comparison between calculated values and measured values it is believed that the moments of inertia can be estimated within 10 percent by use of this method.

Kirschbaum, H. W.

"ESTIMATION OF MOMENTS OF INERTIA OF AIRPLANES FROM DESIGN DATA"

Technical Note No. 575, July 1936, Langley Memorial Aeronautical Laboratory, Hampton, VA.

A method of determining the moments of inertia of an airplane from design data pertaining to the weights and locations of the component parts is described. The computations required to ascertain the center-of-gravity position are incorporated with the calculations of moments of inertia. A complete set of data and calculations for a modern airplane is given to illustrate the procedure. From a comparison between calculated values and measured values it is believed that the moments of inertia can be estimated within 10 percent by use of this method.

Kist, R. A. and Garry, K. P.

"HAZARDS DUE TO HELICOPTER WAKES"

College of Aeronautics Report No. 9311, Dec. 1993, Cranfield University, Bedford, UK

The local velocities induced in the wake of a helicopter can be a serious hazard to light aircraft operating nearby. A theoretical model is developed which makes it possible to estimate the rolling

moment induced on a light aircraft entering the wake of a helicopter. The model shows good agreement with the limited amount of flight test data available. An annotated bibliography of the literature available on helicopter wakes is presented to identify specific areas in which further research is required.

Kitaplioglu, C. and Caradonna, F. X.

"A STUDY OF BLADE-VORTEX INTERACTION AEROACOUSTICS UTILIZING AN INDEPENDENTLY GENERATED VORTEX"

Aerodynamics and Aeroacoustics of Rotorcraft, AGARD-CP-552, August 1995, pp. 20-1 to 20-19.

This paper presents results from an experimental study of rotor blade-vortex interaction (BVI) aerodynamics and acoustics. The experiment utilized an externally generated vortex interacting with a two-bladed rotor operating at zero thrust to minimize the influence of the rotor's own wake. The rotor blades were instrumented with a total of 60 absolute pressure transducers at three spanwise and ten chordwise stations on both the upper and lower surfaces. Acoustic data were obtained with fixed near-field microphones as well as a movable array of far-field microphones. The test was carried out in the acoustically treated test section of the NASA Ames 80- by 120-Foot Wind Tunnel. Several parameters which influence BVI, such as vortex-rotor separation distance, vortex strength, and vortex sense (swirl direction), as well as rotor tip Mach number and advance ratio, were varied. Simultaneous measurements were obtained of blade surface pressure distributions, near-field acoustics, and far-field acoustics during the vortex-blade encounters.

Klaas, M., Schroder, W. and Althaus, W.

"EXPERIMENTAL INVESTIGATION OF SLENDER STREAMWISE VORTICES AND OBLIQUE SHOCK-VORTEX INTERACTION"

AIAA Paper No. 2005-4652, Toronto, Canada, June 2005

Velocity measurements of a slender streamwise vortex and vortex breakdown caused by the interaction of the vortex with an oblique shock (oblique shock-vortex interaction, OSVI) are presented. The circumferential and axial velocity profiles of the supersonic wing tip vortex are measured at two freestream Mach numbers and three locations downstream of the vortex generator for four vortex strengths using a two-component Laser Doppler Velocimetry (LDV) system. The velocity distribution in the interaction region of the vortex and the shock are investigated by Particle Image Velocimetry (PIV) at freestream Mach numbers. In order to obtain information about the global structure of the flow field and unsteady flow phenomena, the flow is visualized using the schlieren technique in conjunction with a high-speed digital video camera. The LDV measurements show the axial Mach number distribution of the vortex to possess a distinct wake-like profile, while the tangential Mach number profile has the shape of an asymmetric Burgers vortex. The experiments also reveal the decay in the swirl ratio of the vortex as it travels downstream. Furthermore, flow visualizations evidence the strong time-dependent

behavior of the flow structure and the existence of a locally normal shock in the vicinity of the vortex core.

Klaas, M., Thomer, O. and Schroder, W.

"EXPERIMENTAL AND COMPUTATIONAL INVESTIGATION OF OBLIQUE SHOCK-VORTEX INTERACTION"

AIAA Paper No. 2002-3305, St. Louis, MO, June 2002

Experimental and numerical results of vortex breakdown caused by the interaction of slender vortices and oblique shocks (oblique shock-vortex interaction, OSVI) are presented. Wind tunnel experiments are conducted at freestream Mach numbers of 2.0 and 2.9. To obtain information about the global structure of the flow field and unsteady flow phenomena, the flow is visualized using a color-schlieren method along with a digital video camera. For a more detailed analysis of the shock-vortex interaction the differential interferometry is applied. The numerical investigation is based on solutions of the Euler and Navier-Stokes equations for unsteady three-dimensional supersonic flow. The experimental and numerical results show the strong time-dependent behavior of the flow structure and evidence the necessity of a locally normal shock in the vicinity of the vortex core to cause vortex breakdown.

Klar, J.-U. and Breitsamter, C.

"UNSTEADY AERODYNAMIC LOADS ON A HIGH-AGILITY AIRCRAFT DUE TO WAKE VORTEX ENCOUNTER"

Journal of Aircraft, Vol. 51, No. 5, September-October 2014, pp. 1511-1521.

The presented investigation focuses on the determination of unsteady aerodynamic loads for different kinds of wake vortex encounters. The wake-generating aircraft is a delta-canard configuration, whereas for the penetration, just a delta wing is considered. Based on extensive experimental and numerical investigations of the wake vortex system of a preceding aircraft, the wake-induced angle of attack on an encountering aircraft is determined. Therefore, the induced flow field of the wake-generating aircraft is transformed into the coordinate system of the penetrating aircraft. Because the unsteadiness results on the one hand from the velocity fluctuations inside the wake, and on the other hand from the relative movement of the two aircraft, the wake problem is split into a discrete and a continuous wake problem. Both problems lead to an unsteady distribution of the angle of attack, which is variable in the chord and spanwise directions. The resulting lift and pitching moment distribution is calculated by an alternative approach in the unsteady lifting surface method. For the discrete wake problem, the resulting loads depend on the heading and bank angle of the penetrating aircraft relative to the vortex axes. In general, negative lift, rolling, and pitching moments can be observed. Their magnitude varies with the encounter maneuver. The continuous wake problem refers to the unsteady loads due to velocity fluctuations inside the wake on an aircraft following the wake-generating aircraft. Thereby, high-frequency forces and moments act upon the following aircraft.

Klar, J.-U., Breitsamter, C. and Adams, N.

"EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF THE WAKE VORTEX SYSTEM OF A DELTA-CANARD-CONFIGURATION"

ICAS 2010, Paper 2010-10.2.4, Sept. 2010, Nice, France.

High-agility aircraft may encounter the wake of a preceding aircraft. The associated loads are influenced by the actual maneuver, the unsteady angle of attack due to the wake encounter and the aircraft structure's dynamic behavior. Experimental and numerical investigations of the wake vortex system of a delta-canard-configuration are presented.

Klar, J.-U., Breitsamter, C., Hickel, S. and Adames, N.

"INTEGRATED EXPERIMENTAL-NUMERICAL ANALYSIS OF HIGH-AGILITY AIRCRAFT WAKE VORTEX EVOLUTION"

Journal of Aircraft, Vol. 48, No. 6, November-December 2011, pp. 2050-2058.

The presented investigation includes a combined experimental-numerical approach to quantify the wake vortex system of a high-agility aircraft from the near field up to the far field. Detailed near-field data are obtained by low-speed wind-tunnel tests on a delta-canard configuration of 1:15 scale. The measurements are performed at several angles of attack applying advanced hot-wire anemometry. For a wake distance of up to 16 wing spans, mean and turbulent velocity fields are measured. The upstream data are used to initialize implicit large-eddy simulations aimed to compute the velocity fields of the wake vortex system over a wake distance of up to 50 spans. Here, a validation case is shown comparing measured and calculated wake data over a distance from 4 to 16 spans, with the implicit large-eddy simulations initialized by the measured quantities at a position of 2 wing spans. Compared with the experimental data, the numerical results show the expected lateral and vertical movement of the wake vortex system due to the interaction of the single vortices. The distributions of axial vorticity, crossflow velocities, and turbulence intensities match well with the experimental data. In addition, the dissipation process can be observed, resulting in a reduction of circulation. In the context of this study, the measured and computed velocity fields will be used to determine unsteady aerodynamic loads acting on a fighter aircraft encountering the wake. This is of great importance as wake induction may result in critical structural dynamic loads.

Kleb, B. and Wood, B.

"CFD: A CASTLE IN THE SAND?"

AIAA Paper No. 2004-2627, June 2004, Portland, OR.

The computational simulation community is not routinely publishing independently verifiable tests to accompany new models or algorithms. A survey reveals that only 22 percent of new models published are accompanied by tests suitable for independently verifying the new model. As the community develops larger codes with increased functionality, and hence increased complexity in terms of the number of building block components and their interactions, it becomes prohibitively expensive for

each development group to derive the appropriate tests for each component. Therefore, the computational simulation community is building its collective castle on a very shaky foundation of components with unpublished and unrepeatable verification tests. The computational simulation community needs to begin publishing component-level verification tests before the tide of complexity undermines its foundation.

Klein, M. A., Lentz, W. K. and Komerath, N. M.

"REDUCTION OF FLUCTUATIONS OVER SWEEPED WINGS USING MINI-FENCES"

AIAA Paper No. 1997-0548, January 1997, Reno, NV.

Passive and active surface devices are used to modify the narrow-band velocity fluctuations over a 59.3-degree delta wing at high angles of attack. Previous work has traced these fluctuations to counter-rotating structures in the shear layer below the post-burst vortex. Small vertical fences placed near the point of origin of the fluctuations attenuate the peak spectral energy by as much as 78 percent. The lift and drag are shown to be unaffected. Fences placed at other locations and orientations show various levels of suppression and amplification. The most effective fence height, position, and orientation for attenuation at 25 deg. angle of attack are identified. An active fence and a ramp modulated at the fluctuation frequency show attenuation corresponding to the effective duty cycle of deployment in a given range of shear layer. It is seen that the fences must extend well beyond the surface boundary layer to be effective, but extending into the central region of the flow is ineffective, further proving that the fluctuations originate in the outer shear layer of the vortex, not in the core.

Klein, R. and Majda, A. J.

"AN ASYMPTOTIC THEORY FOR THE NONLINEAR INSTABILITY OF ANTIPARALLEL PAIRS OF VORTEX FILAMENTS"

Phys. Fluids A, Vol. 5, No. 2, February 1993, pp. 369-379

Simplified asymptotic equations describing the nonlinear dynamics of perturbed pairs of parallel vortex filaments are derived and analyzed here. The derivations are general enough to allow for vortices of unequal strength, but emphasis here is on the antiparallel vortex pair. The simplified asymptotic equations account for both the internal effects of self-induction and self-stretching for each filament and the external effects of mutual induction that lead to a nontrivial coupling of the perturbations of the two filaments. When these nonlinear equations are linearized at the unperturbed filament pair, the linearized stability theory of Crow is recovered in a systematic fashion. The asymptotic equations are derived in a novel singular limit at high Reynolds numbers through assumptions like the authors' recent theories for the dynamics of a single perturbed vortex filament. Through the Hasimoto transform, these equations become two coupled perturbed nonlinear Schrodinger equations for a pair of filament functions. A series of numerical solutions of the asymptotic equations exhibits several new phenomena in the nonlinear instability of pairs of antiparallel vortex filaments.

Klein, R. and Ting, L.

"VORTEX FILAMENT WITH AXIAL CORE STRUCTURE VARIATION"

Applied Mathematics Letters, Vol. 5, Issue 4, July 1992, pp. 99-103.

Using the methods of matched asymptotics with the slenderness ratio ϵ as the expansion parameter, we derive the governing equations for the velocity of the centerline of a slender viscous vortex filament and the evolution of its vortical core structure. In the core, both the circumferential and axial velocity components relative to the centerline of the filament can be $O(1/\epsilon)$ and have axial variations in addition to the rapidly decaying radial variations.

Klein, R., Majda, A. J. and Damodaran, K.

"SIMPLIFIED EQUATIONS FOR THE INTERACTION OF NEARLY PARALLEL VORTEX FILAMENTS"

J. Fluid Mech., Vol. 288, April 1995, pp. 201-248

New simplified asymptotic equations for the interaction of nearly parallel vortex filaments are derived and analyzed here. The simplified equations retain the important physical effects of linearized local self-induction and nonlinear potential vortex interaction among different vortices but neglect other non-local effects of self-stretching and mutual induction. These equations are derived systematically in a suitable distinguished asymptotic limit from the Navier-Stokes equations. The general Hamiltonian formalism and conserved quantities for the simplified equations are developed. Strong evidence is presented that for any filament pair with a negative circulation ratio, there is finite-time collapse in a self-similar fashion independent of the perturbation but with a structure depending on the circulation ratio. On the other hand, strong evidence is presented that no finite-time collapse is possible for perturbations of a filament pair with a positive circulation ratio.

Klein, S., Hoppmann, D., Scholz, P. and Radespiel, R.

"HIGH-LIFT AIRFOIL INTERACTING WITH A VORTICAL DISTURBANCE: WIND-TUNNEL MEASUREMENTS"

AIAA Journal, Vol. 53, No. 6, June 2015, pp. 1681-1692.

This paper describes experimental investigations on the effect of large-scale disturbances interacting with the flow around a two-element airfoil. Quasi two-dimensional transversal vortices are created in a closed wind-tunnel test section shortly after the nozzle. Moving along the test section, these vortices interact with a two-element airfoil in high-lift configuration. Various measurement techniques are used to identify and characterize these complex interactions. The techniques are phase-locked particle image velocimetry, time-resolving five-hole probe, time-resolving static pressure measurements, and time-averaged measurements of the static pressure distribution of the high-lift airfoil. The vortex generation and evolution along the empty wind-tunnel test section is discussed before considering the vortex-airfoil interactions. As a result, the influence of the induced vortices on the time-resolving static

pressure along the airfoil surface and the interaction with the airfoil flap flow is described. The findings are linked to flow field images and the induced flow effects (the circulatory effect and the local velocity effect) are discussed.

Kless, J. E., Aftosmis, M. J., Ning, S. A. and Nemec, M.

"INVISCID ANALYSIS OF EXTENDED-FORMATION FLIGHT"

AIAA Journal, Vol. 51, No. 7, July 2013, pp. 1703-1715.

Flying airplanes in extended formations, with separation distances of tens of wingspans, significantly improves safety while maintaining most of the fuel savings achieved in close formations. The present study investigates the impact of roll trim and compressibility at a fixed lift coefficient on the benefits of extended-formation flight. A Euler solver with adjoint-based mesh refinement combined with a wake propagation model is used to analyze a two-body echelon formation at a separation distance of 30 spans. Two geometries are examined: a simple wing and a wing-body geometry. Energy savings, quantified by both formation-drag fraction and span efficiency factor, are investigated at subsonic and transonic speeds for a matrix of vortex locations. The results show that, at fixed lift and trimmed for roll, the optimal location of vortex impingement is about 10 percent inboard of the trailing airplane's wing tip. Interestingly, the improvement in drag fraction is relatively robust in the vicinity of the optimal position. Over 90 percent of energy benefits can be obtained with a 5 percent variation in vertical and 10 percent variation in spanwise positions. Control surface deflections required to achieve roll trim reduce the benefits of formation flight by 3-5 percent at subsonic speeds and 9-11 percent at transonic speeds. Overall, simulations show peak induced drag saving for the trail aircraft are 54 percent in subsonic flow and 35 percent in transonic flow while accounting for trim.

Klewicki, J., Fife, P. and Wei, T.

"ON THE LOGARITHMIC MEAN PROFILE"

Journal of Fluid Mechanics, Vol. 638, 2009, pp. 73-93.

Elements of the first-principles-based theory are clarified and their veracity tested relative to the properties of the logarithmic mean velocity profile. While the approach employed broadly reveals the mathematical structure admitted by the time averaged Navier-Stokes equations, results are primarily provided for fully developed pressure driven flow in a two-dimensional channel. The theory demonstrates that the appropriately simplified mean differential statement of Newton's second law formally admits a hierarchy of scaling layers, each having a distinct characteristic length. The theory also specifies that these characteristic lengths asymptotically scale with distance from the wall over a well-defined range of wall-normal positions, y . Numerical simulation data are shown to support these analytical findings in every measure explored. The mean velocity profile is shown to exhibit logarithmic dependence (exact or approximate) self-similarity from layer to layer within the hierarchy. The condition of pure self-similarity corresponds to a constant leading coefficient in the logarithmic mean velocity equation. The theory predicts and clarifies why logarithmic behavior is better approximated as

the Reynolds number gets large. An exact equation for the leading coefficient (von Karman coefficient κ) is tested against direct numerical simulation data. Two methods for precisely estimating the leading coefficient over any selected range of y are presented. These methods reveal that the differences between the theory and simulation are essentially within the uncertainty level of the simulation. The von Karman coefficient physically exists owing to an approximate self-similarity in the flux of turbulent force across an internal layer hierarchy. Mathematically, this self-similarity relates to the slope and curvature of the mean vorticity profile. The theory addresses how why and under what conditions logarithmic dependence is approximated relative to the specific mechanisms contained within the mean statement of dynamics.

Kliment, L. K.

"DYNAMICS OF LONGITUDINAL WAKE VORTICES"

PhD Thesis, July 2009, Wichita State Univ., Wichita, Kansas.

In the present study, the mid-field vortex wake is investigated. For the most part, the results focus on the motion of a pair of co-rotating vortices prior to merger, both in and out of ground effect. However, in order to verify the experimental and computational methods, results for single vortices, counter-rotating pairs, and complex wakes are also presented. A method is presented which allows measurement of the time dependent motion of vortex filaments. This optical method interferes minimally with the wake and allows recording of vortex location and time-dependent motion. From the position and time information recorded, extraction of the amplitudes of motion, core motion, spiraling behavior, vortex strengths, and the principal planes of motion is possible. First, a single vortex is studied to establish a basis for comparison. The dye remains in the core and the motion of a single vortex is shown to exhibit a growth in amplitude with increasing downstream distance and strength. The core motion is shown to be minimal, remaining smaller than one core diameter. In addition, when the single vortex is forced to oscillate at a given frequency, the dye remains in the core, even though the amplitudes of motion are large. The forcing frequency is identified easily against the background noise. Two four-vortex cases are then presented. The first case consists of filaments that spiral while in the second they scatter. These results are consistent with those shown in literature and show that the experimental method can be used for analyzing complex wakes. Pairs of unforced, co-rotating filaments are studied outside of ground effect. The constant rate of spiraling is shown to increase as the vortex strength increases and vortex span decreases. Vortex span either remains constant or decreases with downstream distance depending on the vortex separation distance. The motion of the center of spiraling is shown to be minimal, similar to the motion of the vortex core in the single-vortex cases. Ground effect is then considered for counter-rotating vortices, because there is a wealth of information on this topic in the literature. When counter-rotating vortices are near a ground plane, a lateral drift as well as a rebounding behavior is present.

Kliment, L. K. and Rokhsaz, K.

"EXPERIMENTAL INVESTIGATION OF THE FORCED RESPONSE OF A PAIR OF CO-ROTATING VORTEX FILAMENTS"

AIAA Paper No. 2004-2434, Portland, OR, June-July 2004.

The interactions of pairs of co-rotating vortex filaments have been investigated in a water tunnel. The time history of the motion of each filament has been recorded at several downstream locations to analyze its spatial and temporal behavior. The vortices have been excited over a range of frequencies using a shaker. The filaments have been shown to move along preferred directions, suggesting their tendency to form planar waves. The amplitudes of these waves have been shown to grow, implying unstable interaction between the vortices. The angles of the planes containing the motion have been presented and compared with analytical prediction. The flow is shown to contain all the essential features predicted by two analytical models.

Kliment, L. K. and Rokhsaz, K.

"EXPERIMENTAL INVESTIGATION OF PAIRS OF VORTEX FILAMENTS IN GROUND EFFECT"

J. Aircraft, Vol. 45, No. 2, March-April 2008, pp. 622-629

The motion of corotating filaments in ground effect is investigated using a water tunnel. The vortices are generated using two flat blades and the ground is modeled with a splitter plate. The time history of the vortex motion is recorded at several downstream locations. Data are shown for two ground-plane positions and compared with the vortex behavior in the freestream. The experimental data are also compared with a potential-flow model. Results show that the vortices undergo a rebound as the result of ground effect. The vortices also undergo a lateral motion due to potential-flow effects. A leapfrogging behavior is present due to the differences in the lateral motions caused by the ground proximities of the spiraling vortices. In addition, the filaments form planar waves and move along preferred directions.

Kliment, L. K. and Rokhsaz, K.

"PRELIMINARY INVESTIGATION OF A COMPLEX AIRCRAFT WAKE VORTEX CONFIGURATION"

AIAA Paper No. 2003-3600, Orlando, FL, June 2003

The interactions between two sets of co-rotating vortex filaments are investigated experimentally. The experiments are carried out in a water tunnel. Two specific cases are addressed; one in which the filaments on each side spiral around one another, and a second case in which the filaments on each side scatter. In the spiraling case, a simple method is introduced to determine the vortex strengths from the experimental data. Also, in this case, it is demonstrated that the mutual induction between the vortices leads to oscillations of the filaments with a preferred direction of motion that rotates at the same rate as the orbiting rate. The experimental data shown indicates that in the scattering case, the filaments close to each other exhibit a Crow-type of motion, while those farther apart retain the

characteristics of isolated filaments. These results are in complete agreement with those obtained earlier concerning the behavior of single and co-rotating vortices.

Kliment, L. K. and Rokhsaz, K.

"INFLUENCE OF TERRAIN ROUGHNESS ON TRAILING VORTICES IN GROUND EFFECT"

AIAA Paper No. 2007-4365, Miami, FL, June 2007

The spatial and temporal behaviors of counter-rotating vortex filaments in ground effect have been investigated experimentally in a water tunnel over a range of thirteen span lengths. The vortices have been generated using two flat blades and the ground has been modeled with a splitter plate. Streamwise ridges of varying height and spacing have been added to the ground plane and their effects on vortex trajectories and vortex meandering have been studied. Three sets of data are presented that include different vortex strengths and vortex spans, in addition to variations in the ground roughness. In comparison with the results for a smooth ground plane, vortex trajectories, their preferred direction of motion, and the rate of growth of their amplitudes of motion have been shown to be insensitive to terrain roughness.

Kliment, L. K. and Rokhsaz, K.

"EFFECT OF GROUND ROUGHNESS ON AIRCRAFT TRAILING VORTICES"

Proceedings of 3rd Annual GRASP Symposium, Wichita State University, 2007, pp. 185-186.

Experiments were performed in a water tunnel to study the effect of terrain roughness on the spatial and temporal behavior of trailing vortices. Without ground roughness, the spatial behavior was consistent with data in the current literature. The ground roughness had negligible effect on the position of the vortices and their temporal behavior. These results were based on one combination of vortex span and ground roughness. Other combinations may lead to different results.

Kliment, L. K., Miller, T. S. and Rokhsaz, K.

"DYNAMICS OF COROTATING VORTEX FILAMENTS PART 2: EXPERIMENTAL RESULTS"

Journal of Aircraft, Vol. 44, No. 1, January-February 2007, pp. 100-105

The interactions of pairs of corotating vortex filaments have been investigated experimentally in a water tunnel. The time history of the motion of each filament has been recorded at several downstream locations to analyze its spatial and temporal behavior. Two sets of data are presented in which the vortices have been excited over a range of frequencies using a shaker. The excitation frequency and its multiples have been shown to be present in the downstream flow. At each downstream position, the filaments have been shown to move along preferred directions, suggesting their tendency to form planar waves, inclined relative to the line connecting them. The amplitudes of these waves have been shown to grow, implying unstable interaction between the vortices. The angles

of the planes containing the motion have been presented and compared with the predictions of two analytical models. The scatter in the data prevented quantitative comparison with the analytical predictions. However, the flow is shown to contain all of the essential features predicted by two analytical models.

Klinge, F., Kirmse, T. and Kompenhans, J.

"INVESTIGATION OF THE DENSITY AND VELOCITY DISTRIBUTION OF A WING TIP VORTEX BY MEANS OF STEREOSCOPIC BACKGROUND ORIENTED SCHLIEREN METHOD (BOS) AND STEREOSCOPIC PARTICLE IMAGE VELOCIMETRY (PIV)"

The Calouste Gulbenkian Foundation, 12th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 2004

A wind tunnel wing tip vortex test combining the techniques of Background Oriented Schlieren (BOS) and Particle Image Velocimetry (PIV) is described. The combined techniques provide simultaneous density and velocity measurements of the vortex field.

Klinge, F., Kirmse, T. and Kompenhans, J.

"APPLICATION OF QUANTITATIVE BACKGROUND ORIENTED SCHLIEREN (BOS): INVESTIGATION OF A WING TIP VORTEX IN A TRANSONIC WIND TUNNEL"

Proceedings of PSFVIP-4, Chamonix, France, June 2003, pp. 1-11

Background Oriented Schlieren (BOS) measurements have been performed in combination with Particle Image Velocimetry (PIV) measurements in order to derive quantitative flow velocity and density data of a wing tip vortex generated by an airfoil model of a modern large transportation aircraft in the transonic wind tunnel (TWG) of the German-Dutch wind tunnel (DNW) in Gottingen. The model has a span of 0.6m and a wing area of 0.1m squared. The test was performed in the 1 x 1m transonic test section of the TWG with different flow Mach numbers ($Ma = 0.5 / 0.6 / 0.7$). The measurement technique BOS is still under development, nevertheless local quantitative density measurements in 2D flows are already possible. This test was performed to prove the applicability of BOS to 3D axis symmetrical flows in real wind tunnel experiments as well as the applicability of three component PIV measurements in transonic flows. The measurement system (BOS and PIV) consists of 4 digital cameras and a double pulsed Nd:YAG laser with 2x320mJ. This paper focuses on the theoretical as well as on the technical aspects of the BOS recording and evaluation methods especially for 3D axis symmetrical flows.

Klinge, F., Pallek, D. and Kompenhans, J.

"DEVELOPMENT OF STEREOSCOPIC BACKGROUND ORIENTED SCHLIEREN METHOD (BOS) AND LASER LIGHT SHEET TECHNIQUE (ILS) FOR STUDY OF REYNOLDS NUMBER EFFECTS ON WING TIP VORTEX POSITIONS UNDER CRYOGENIC CONDITIONS"

13 International Symposium on Applied Laser Techniques to Fluid Mechanics, Lisbon, Portugal, June 2006

Wake vortex turbulence induced by large transport aircrafts is problematic for airports capacity because of their hazardous impact on following aircraft. Safety rules defining minimum distances between landing and taking off aircrafts are based on the strength and temporal duration of dissipation of the vortex turbulence. The wing tip vortex position is of major interest because interactions with vortices generated from e.g. the elevator of the airplane are desired to accelerate their decay. Experimental data are needed to enable quick and accurate vortex modelling. These data are coming up to now mostly from wind tunnels which cannot simulate the 'real' Reynolds and Mach number. Thereby it is usually assumed that this mismatch does not affect the results. Klinge et al showed that wing tip vortices can be localized quantitatively with high accuracy during wind tunnel tests by means of stereoscopic BOS and additional software tools. The objective of this experiment was to find out, whether the Reynolds number has a significant impact on the vortex position of a wing tip vortex.

Kloosterman, M. H. M.

"DEVELOPMENT OF THE NEAR WAKE BEHIND A HORIZONTAL AXIS WIND TURBINE, INCLUDING THE DEVELOPMENT OF A FREE WAKE LIFTING LINE CODE"

MS Thesis, June 2009, Delft University of Technology, Delft, The Netherlands.

A lot of research has been carried out in the past on wind turbine wake aerodynamics. Models exist for both the near field and the far field. The near wake is governed by a typical vortex structure that gradually decays due to viscous and turbulent mixing effects, forming the less structured far wake region. The formation of the far field from the rotor region and near wake is not completely understood yet. In this thesis an attempt is made to develop a simple model that tries to capture the decay of the vortex wake within the first two diameters downstream of the rotor. A free wake lifting line vortex model has been developed. Viscous effects have been added to the vortex code in the form of vortex core models and a simple model that describes the turbulent decay of circulation as a function of ambient turbulence intensity. Furthermore, models for simulating wind shear and the presence of the nacelle have been implemented. A thorough validation study of the model has been carried out by means of hot-film and Particle Image Velocimetry (PIV) measurements. Close to the rotor the model compares well with the measured induced velocities measured with a hot-film. PIV measurements show that the model captures the position of the tip vortex quite well within the first diameter downstream. The measured velocity field can however not be reproduced correctly by the code. No measurements were available that can validate the turbulent decay of the vortex wake; instead, suggestions are made for an experiment in the Open Jet Facility of Delft University of Technology. The new model is only valid in the region of the wake where the vortex structure of the wake is still intact which is typically between one or two diameters downstream. Further downstream the outputs from the model may be used as an input for a Reynolds Averaged Navier-Stokes model that describes the far wake of the rotor.

Knio, O. M., Collorec, L. and Juve, D.

"NUMERICAL STUDY OF SOUND EMISSION BY 2D REGULAR AND CHAOTIC VORTEX CONFIGURATIONS"

Journal of Computational Physics, Vol. 116, 1995, pp. 226-246

The far-field noise generated by a system of three Gaussian vortices lying over a flat boundary is numerically investigated using a two-dimensional vortex element method. The method is based on the discretization of the vorticity field into a finite number of smoothed vortex elements of spherical overlapping cores. The elements are convected in a Lagrangian reference along particle trajectories using the local velocity vector, given in terms of a desingularized Biot-Savart law. The initial structure of the vortex system is triangular; a one-dimensional family of initial configurations is constructed by keeping one side of the triangle fixed and vertical, and varying the abscissa of the centroid of the remaining vortex. The inviscid dynamics of this vortex configuration are first investigated using non-deformable vortices. Depending on the aspect ratio of the initial system, regular or chaotic motion occurs. Due to wall-related symmetries, the far-field sound always exhibits a time independent quadrupolar directivity with maxima parallel and perpendicular to the wall. When regular motion prevails, the noise spectrum is dominated by discrete frequencies which correspond to the fundamental system frequency and its super harmonics. For chaotic motion, a broadband spectrum is obtained; computed sound levels are substantially higher than in non-chaotic systems. A more sophisticated analysis is then performed which accounts for vortex core dynamics. Results show that the vortex cores are susceptible to inviscid instability which lead to violent vorticity reorganization within the core. This phenomenon has little effect on the large-scale features of the motion of the system or on low frequency sound emission. However, it leads to the generation of a high-frequency noise band in the acoustic pressure spectrum. The latter is observed in both regular and chaotic system simulations.

Knox, C. E.

"AN INVESTIGATION OF AIR TRAFFIC CONTROL PROCEDURES AND PILOT TECHNIQUES IN A HIGH DENSITY TERMINAL AREA"

Ph.D. Thesis, 1974, Kansas University, Lawrence, KS

An investigation was conducted to determine if increases in runway capacity could be achieved through the modification of various air traffic control procedures and pilot techniques. Modified procedures and techniques were to be specified such that equipment not already necessary for IFR and/or VFR flight in a high density, semi-positive controlled airspace would not be required. A summary of pertinent pilot and air traffic controller constraints and airspace structure around the high-density terminal area and a review of wake vortex characteristics and avoidance procedures was included in this investigation. Kinematic equations of motion and aircraft performance equations were developed for take-off, landing, and in-flight maneuvering computations.

Knox, J. A., Black, A. W., Rackley, J. A., Wilson, E. N., Grant, J. S., Phelps, S. P., Nevius, D. S. and Dunn, C. B.

"AUTOMATED TURBULENCE FORECASTING STRATEGIES"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 12, 2016, Springer International Publishing Switzerland, pp. 243-260.

Forecasting aviation turbulence remains a challenge in the twenty-first century because of the small temporal and spatial scales of the phenomenon and the multiplicity of causes of the turbulence. In this chapter we discuss both the theoretically derived methods and the empirical techniques used to forecast aviation turbulence. The focus is mainly on clear-air turbulence (CAT), but forecasting techniques for low-level, convectively induced, and mountain wave turbulence (MWT) are also surveyed. We conclude with a brief glimpse into the future of aviation turbulence forecasting.

Ko, N. W. M., Leung, R. C. K. and Tang, C. C. K.

"THE INTERACTION OF PERTURBED VORTEX RINGS AND ITS SOUND GENERATION. PART II"

Journal of Sound and Vibration, Vol. 228, Issue 3, December 1999, pp. 511-541.

The present work extends the study of interactions of two coaxial vortex rings of thin cores with azimuthal instability to wavenumber range m less than or equal to 11 or greater than or equal to 6. Unstable modes are found at m less than or equal to 10 or greater than or equal to 6. Stable mode is found only at $m = 11$. The present range of unstable wavenumbers m

Kocer, G., Chokani, N. and Abhari, R. S.

"DETAILED MEASUREMENTS IN THE WAKE OF A 2MW WIND TURBINE"

European Wind Energy Association 2012 Conference, April 2012, Copenhagen, Denmark.

Detailed, high-resolution measurements with a UAV upstream and in the wake of a full-scale wind turbine located in complex terrain are reported. The wake centerline velocity deficit measurements made with UAV are compared to wind tunnel measurements with a subscale wind turbine in a non-uniform velocity profile and simulated thermal stratification and surface roughness. The comparison shows good agreement. Upstream velocity profiles measured with the UAV are also compared to measurements made with a LIDAR profiler. Comparison of total velocity profiles showed good agreement whereas the horizontal speed shows discrepancy due to the uniform flow assumption that is used in LIDAR profiler measurements. Comparison of the predicted velocity field from the recently developed ETH Zurich Wake Model and wake measurements made with the UAV are also shown. There is overall good agreement between the model and the UAV measurements.

Koch, G. J., Barker, B. C. and Britt, C. L.

"DEVELOPMENT OF AN OPERATIONAL WAKE VORTEX SENSOR BASED ON PULSED COHERENT LIDAR"

9th Conference on Coherent Laser Radar, Paper Th3, Linkoping, Sweden, June 1997

An overview is given of NASA Langley's development of pulsed lidar for a operational wake vortex sensor. Data is presented from aircraft landings at JFK International Airport and Norfolk International Airport. The lidar system, including several generations of lasers, is presented. Future field deployments and project goals are discussed.

Koch, G. J., Beyon, J. Y., Barnes, B. W., Petros, M., Yu, J., Amzajerdian, F., Kavaya, M. J. and Singh, U. N.

"HIGH-ENERGY 2 MICRON DOPPLER LIDAR FOR WIND MEASUREMENTS"

Optical Engineering, Vol. 46, No. 11, November 2007, pp. 116201-1 - 116201-14.

A coherent Doppler lidar at 2 micron wavelength has been built with higher output energy (100 mJ) than previously available. The laser transmitter is based on diode-pumped Ho:Tm:LuLiF, a recently developed laser material that allows more efficient energy extraction. Single-frequency operation is achieved by a ramp-and-fire injection seeding technique. An advanced photodetector architecture is used incorporating photodiodes in a dual-balanced configuration. A digital signal processing system has been built, allowing real-time display of wind and aerosol backscatter data products. The high pulse energy and receiver efficiency provides for measurement of wind fields to ranges not seen before with 2- micron lidars, and example wind measurements were made to show this capability.

Koch, G. J., Murray, J., Lytle, C. and Nguyen, C.

"A 1000 HZ PULSED SOLID-STATE RAMAN LASER FOR COHERENT LIDAR MEASUREMENT OF WAKE VORTICES"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 292-298.

A coherent lidar based on a Raman shifted Nd laser is under development with parameters optimized for wake vortex detection. Specifications for the laser are a wavelength of 1.56 microns, pulse repetition frequency of 1000 Hz, pulse width of 1000 ns, and pulse energy of 10 mJ. Range and resolution capabilities are discussed as well as preliminary designs for the laser, receiver, and signal processor.

Koch, G., Staton, L. and Nguyen, C.

"DESIGN CONSIDERATIONS FOR AN OPERATIONAL WAKE VORTEX LIDAR SENSOR AT 2-MICRON WAVELENGTHS"

Optical Society of America, Technical Digest Series, Vol. 19, No. TuD4-1, 1995, pp. 190-192

The lidar is envisioned to be a coherent Doppler system located in the terminal area. Since the lidar will be operating in an environment where people may be exposed to the beam, unconditional eye safety is a further constraint. Because of this eye safety requirement and in consideration of recent advances in solid-state laser development, our baseline lidar design is for a 2-micron based coherent lidar. Extensive system studies are underway to set the specifications for the lidar, such as pulse width, pulse energy, pulse repetition frequency, waveform modulation, and scanning requirements.

Koch, M. E. and Buchholz, A.

"QUANTITATIVE ANALYSIS OF AIRCRAFT HEIGHT ON FINAL APPROACH"

IEEE/AIAA 30th Digital Avionic Systems Conference, Paper 1A4, October 2011, Seattle, WA.

Wake turbulence encounters are a significant risk to pilots, and rules and guidance exist to ensure the safety of all aircraft operating in the National Airspace System. In poor weather and in airspace serviced by surveillance and Air Traffic Control (ATC). ATC is responsible for separating aircraft from one another, and a conservative set of standards, including consideration of lead aircraft wake category, ensures the safety of all aircraft without requiring any input from the pilots. In good weather, when separation responsibility has been delegated to flight crews, pilots can use the situation awareness provided by direct visual contact to decrease separation between aircraft, increasing capacity to the nation's airports. One way pilots avoid wake encounters during decreased-separation situations is by adjusting their trajectory with respect to the airplane they are following on final approach. Previous efforts have obtained qualitative feedback from pilots on their wake avoidance strategies. This paper examines actual track data from multiple sources to determine how aircraft behave in real operations for approaches to single runways as well as closely spaced parallel runways. Results confirm that pilots of smaller aircraft, generally those below about 100,000 pounds (lbs) maximum takeoff weight (MTOW), ride higher than the leading aircraft in visual conditions, whereas those over the 100,000 lbs MTOW tend not to modify their approach trajectory. Sensitivity to various parameters such as lead aircraft type, weather, distance between aircraft, and airport are examined in detail.

Kocks, S., Bode, S., Feuerle, T., Paetzold, C., Schoenhals, S. and Hecker, P.

"AN INTEGRATED WAKE VORTEX VISUALIZATION CONCEPT FOR EXISTING COCKPIT DISPLAY SYSTEMS"

Paper EN-022, Second ENRI International Workshop on ATM/CNS, EIWAC 2010, November 2010, Tokyo, Japan.

Major hub airports often operate at their capacity limit and will become more and more the bottlenecks of the air transport network. Among other factors, conservative wake vortex separations during approach and takeoff have a significant impact on an airport's operation efficiency. One possibility to increase capacity is the delegation of separation responsibility from the air traffic controller to the flight crew. However, to guarantee safe operations the pilots must obtain full situational awareness of their environment including potentially hazardous vortex traffic. This paper introduces a concept for the graphical provision of wake vortex hazard areas in existing cockpit displays.

The chosen approach has been realized and integrated into an Airbus A320 cockpit simulator at the Institute of Flight Guidance of the Technische Universitaet Braunschweig. An overview of the institute's simulation environment is given, followed by a presentation of the chosen visualization concept. Results of first evaluations with pilots of commercial and general aviation are summarized. Finally, future work and further developments are addressed.

Kocster, S., Cook, R. and Barbcc, B.

"WINDMILL INTERACTION WITH A VORTEX WAKE"

ASE 463 Q, University of Texas at Austin, Austin, TX, 2003

The purpose of this study is to analyze the effects of descending vortices from high-speed, low altitude, large aircraft on a ground-based windmill. In particular, the goal is to demonstrate a basis for determining the capacity, or lack thereof, of such vortices to damage the windmills. The approach is to model this situation in a laboratory setting by simulating a vortex, translating it through a windmill model outfitted with strain gages, recording bending strains, conducting digital photography of the windmill's motion, and drawing conclusions based on the analysis of all gathered data. Several methods of actual vortex generation were examined and found to be inadequate, although vortex scaling parameters and velocity profiles were computed. Therefore, it was decided to simulate the key features of the vortex with two opposing airflows generated by ducted centrifugal fans. A standard American Style windmill model was purchased from The American Wind Power Center and has been instrumented with strain gages, and two 435 CFM centrifugal fans have been purchased from the Dayton Company. Designs for the fan ducts and the experimental setup have been completed. The next engineering team will be able to proceed by setting up a data acquisition system, building the experimental apparatus, conducting tests, and recording and analyzing data.

Kocurek, J. D. and Tangler, J. L.

"A PRESCRIBED WAKE LIFTING SURFACE HOVER PERFORMANCE ANALYSIS"

Journal of the American Helicopter Society, Vol. 22, No. 4, Issue 1, 1977, pp. 24-35.

The application of lifting surface theory to the calculation of rotor hover performance and the development of an improved prescribed wake representation resulting from schlieren flow visualization studies of model rotor wakes are described. Qualitative comparisons between lifting line and lifting surface methods show the tendency of the lifting line to react excessively when a vortex passes close to a blade. The flow visualization studies reveal wake sensitivity to thrust coefficient, number of blades, and twist not identified in previous investigations. The need to include a recirculation mechanism in the analytical model to provide inflow in addition to that available from the prescribed wake structure is established. A possible source of the recirculation is demonstrated to be the result of vortex interaction and wake expansion immediately below the well-defined near wake.

Kodis, R. D.

"WAKE VORTEX SENSORS"

FAA Symposium on Turbulence, Federal Aviation Administration, Washington, DC, March 1971, p. 28

The results obtained to date on the Transportation Systems Center task to identify remote sensing techniques to detect, locate, and measure wake vortices near the ground is presented. A simple bistatic radar that detects pulses of acoustic radiation deflected by a vortex is described and experimental data shown. Sensors that use electromagnetic signals scattered by particulate matter in wake vortices are indicated to be feasible but would probably prove less acceptable at airports due to their cost, potential hazard, and difficult maintenance.

Kodis, R. D.

"THE DETECTION OF AIRCRAFT WAKE VORTICES"

Conference Proceedings on Flight in Turbulence, AGARD, Number 140, 1973, pp. 11-1 to 11-9

The trailing vortices deposited in the wakes of heavy jet aircraft constitute a serious hazard for encountering aircraft. In the terminal area this hazard leads to longer separation standards and reduced runway capacity. To shorten the required separations without compromising safety it is necessary to be able to detect the presence and the motion of vortices in regions where they constitute a threat. This paper reviews sensing techniques that have been developed and tested for this purpose. In particular, the characteristics of acoustic and wind pressure sensors developed by the U.S. Transportation Systems Center for the Federal Aviation Administration will be described in detail.

Kodis, R. D.

"REMOTE SENSING TECHNIQUES FOR OBSERVING WAKE VORTICES NEAR THE GROUND"

AIAA Paper No. 1975-0320, Washington, DC, 1975

The advent of heavy jet aircraft has made it necessary to develop remote sensors capable of detecting and tracking wake vortices for the purposes of data collection and traffic control. Active sensors now being evaluated include acoustic and optical radars. Passive wind sensors that respond to the velocity field of a nearby vortex have also proved their usefulness. The full complement of such sensors which have been engineered and installed at the Kennedy International Airport (JFK) are described. Typical data are presented and the performance characteristics and limitations of each sensor technique are discussed. Possible application to air traffic operations is indicated.

Kodis, R. D.

"WAKE VORTEX SENSING"

Proceedings of the 18th International Aerospace Instrumentation Symposium, Instrument Society of America, Vol. 18, 1972, pp. 281-283

Experimental studies and tests are reported on two wake vortex sensing techniques designed to sense the presence and track the motions of low altitude aircraft wake vortices endangering operations around terminal areas. The techniques studied are based on acoustic pulse deflection and velocity field measurements.

Koenig, R.

"AIRCRAFT RESPONSE AND PILOT BEHAVIOUR DURING A WAKE VORTEX ENCOUNTER PERPENDICULAR TO THE VORTEX AXIS"

AGARD, Flight in Adverse Environmental Conditions, September 1989

Vortex systems can be hazardous to trailing aircraft which encounter them in flight. The greatest hazard occurs in areas where aircraft from a wide range of classes operate and where the flight paths are close to the ground. Upwash velocities induced by the wake vortices can be equivalent to the design gust velocities. Furthermore, different types of hazardous effects exist when encountering the vortex system, such as imposed rolling and pitching moments, a loss of rate of climb, a loss of altitude and structural loads. Aircraft response and pilot behavior during takeoff are described when a wake vortex is encountered perpendicular to the vortex axis. The aircraft response is calculated by nonlinear digital simulation with a mathematical model of a wake vortex system close to the ground. This real-time vortex model is also used in the Boeing B-737 simulator of Deutsche Lufthansa to examine the pilot behavior. Close to the ground, the wake vortex system induces additional horizontal velocities. There exists a critical flight path where very large g-loads are induced by vertical and horizontal vortex velocities and normal vertical acceleration shortly after takeoff. Often the pilot will attempt to counteract these g-loads, but this produces only a small effect.

Kohl, R. E.

"MODEL EXPERIMENTS TO EVALUATE VORTEX DISSIPATION DEVICES PROPOSED FOR INSTALLATION ON OR NEAR AIRCRAFT RUNWAYS"

NASA CR-132365, August 1973, Hydronautics Inc., Laurel, MD

The effectiveness of various vortex dissipation devices proposed for installation on or near aircraft runways is evaluated on basis of results of experiments conducted with a 0.03-scale model of a Boeing 747 transport aircraft in conjunction with a simulated runway. The test variables included type of vortex dissipation device, mode of operation of the powered devices, and altitude, lift coefficient, and speed of the generating aircraft. A total of fifteen devices was investigated. The evaluation is based on time sequence photographs taken in the vertical and horizontal planes during each run.

Koken, M.

"THE EXPERIMENTAL DETERMINATION OF THE MOMENT OF INERTIA OF A MODEL AIRPLANE"

Honors Research Projects, 585, Fall 2017, The University of Akron, Akron, OH.

This paper describes an experimental setup that can be used to measure the moment of inertia for a model airplane, and it validates the setup by measuring the moment of inertia on a wooden block.

Kokurin, M. and Rokhsaz, K.

"SEMI-ANALYTICAL VISCOUS TRAILING VORTEX-GROUND INTERACTION AND COMPARISON WITH AVOSS MODEL"

AIAA Paper 2017-3036, June 2017, Denver, CO.

A two-dimensional, physics-based model was created and used to analyze the motion of a wake vortex pair with and without the presence of crosswind. The model is used to compute boundary layer separation on the ground plane. Thwaites' and Head's methods are used for boundary layer calculations along with Michels criterion for transition. The results are compared favorably with those from the AVOSS model.

Kolar, V.

"VORTEX IDENTIFICATION: NEW REQUIREMENTS AND LIMITATIONS"

International Journal of Heat and Fluid Flow, Vol. 28, 2007, pp. 638-652

Firstly, a brief survey dealing with popular vortex-identification methods is presented. The most widely used local criteria (applied point by point) - sharing a basis in the velocity-gradient tensor are treated more thoroughly to recall their underlying ideas and physical aspects. Many recent papers have pointed out various applicability limitations of these popular schemes and formulated (explicitly or implicitly) new general requirements, for example: validity for compressible flows and variable-density flows, determination of the local intensity of swirling motion, vortex-axis identification, non-local properties, ability to provide the same results in different rotating frames, etc. Other quite natural requirements are pointed out and added to those already mentioned. Secondly, the vortex-identification outcome of the proposed triple decomposition of the relative motion near a point is presented. The triple decomposition of motion based on the extraction of a so-called 'effective' pure shearing motion - has been motivated by the fact that vorticity cannot distinguish between pure shearing motions and the actual swirling motion of a vortex. This decomposition technique results in two additive vorticity parts (and, analogously, in two additive strain-rate parts) of distinct nature, namely the shear component and the residual one. The residual vorticity represents a direct measure of the actual swirling motion of a vortex. The new kinematic vortex-identification method is discussed on the background of previous methods and general vortex-identification requirements (illustrative examples are included).

Kolar, V. and Sistek, J.

"COROTATIONAL AND COMPRESSIBILITY ASPECTS LEADING TO A MODIFICATION OF THE VORTEX-IDENTIFICATION Q-CRITERION"

AIAA Journal, Vol. 53, No. 8, August 2015, pp. 2406-2410.

The 3-D modification of the vortex-identification Q-criterion, labeled (Q sub M)-criterion, has been proposed. It is based on the corotational and compressibility arguments, and in this regard, it represents a one-way extension from 2-D to 3-D concept. The (Q sub M)-criterion has been successfully applied to different flow situations: it closely reproduces the results of some widely used methods in regions of low external shear and performs better in regions of strong shearing similarly as the average-corotation method. The popular schemes Q and λ^2 tend to interpret the high shear zones of flat plate near wakes behind sharp edges in a biased manner as vortices. These schemes also produce much noisier outcome for the transonic flow past a turbine cascade. Similarity of results between the (Q sub M)-criterion and the average-corotation scheme is understandable due to the common corotational background. Finally, while the average corotation is a vectorial quantity and, therefore, more informative, an appealing aspect of the proposed (Q sub M)-criterion is its ease of evaluation.

Kolar, V., Sistek, J., Cirak, F. and Moses, P.

"AVERAGE COROTATION OF LINE SEGMENTS NEAR A POINT AND VORTEX IDENTIFICATION"

AIAA Journal, Vol. 51, No. 11, November 2013, pp. 2678-2694.

An easy-to-interpret kinematic quantity measuring the average corotation of material line segments near a point is introduced and applied to vortex identification. At a given point, the vector of average corotation of line segments is defined as the average of the instantaneous local rigid-body rotation over 'all planar cross sections' passing through the examined point. The vortex-identification method based on average corotation is a one-parameter, region-type local method sensitive to the axial stretching rate as well as to the inner configuration of the velocity gradient tensor. The method is derived from a well-defined interpretation of the local flow kinematics to determine the 'plane of swirling' and is also applicable to compressible and variable-density flows. Practical application to direct numerical simulation datasets includes a hairpin vortex of boundary-layer transition, the reconnection process of two Burgers vortices, a flow around an inclined flat plate, and a flow around a revolving insect wing. The results agree well with some popular local methods and perform better in regions of strong shearing.

Kolasch, A. and Breitsamter, C.

"VORTEX-FLOW MANIPULATION ON A GENERIC DELTA-WING CONFIGURATION"

Journal of Aircraft, Vol. 51, No. 5, September-October 2014, pp. 1380-1390.

The manipulation of characteristic vortex-flow instabilities, which occur in the flow around delta wings, is of great interest for increasing the performance of such configurations. This work presents experimental results of vortex-flow manipulation on a generic delta-wing configuration using pulsed blowing slot actuators along the leading edge. The frequencies of the examined blowing cases are chosen on the basis of unsteady characteristics that occur in the shear-layer roll-up during vortex formation and vortex breakdown. The results of hot-wire measurements substantiate the receptivity of the shear layer for the pulsed excitation until into the vortex core. The flow field response to this periodic forcing is shown by the displacement of the vortex bursting location in a chordwise direction, thus satisfying the aim of enhancing the aerodynamic performance.

Kollmann, W.

"ACCURATE NUMERICAL SIMULATIONS OF VORTEX FLOWS. I: VORTEX BREAKDOWN"

Computers and Fluids, Vol. 41, 2011, pp. 103-109.

Vortex breakdown in uniform axial flow is investigated numerically by solving the Navier-Stokes equations using a hybrid spectral finite difference method. Two Reynolds numbers and a high swirl number are considered with the lower Re-number resulting in axisymmetric flow, that possesses an asymptotic state, and a higher Re-number, that leads to unsteady flow and a moderate spectral range. The structural properties of the vorticity field are analyzed in terms of vorticity lines and surfaces. A recirculation bubble and a wake emerge that undergo significant fluctuations.

Kollmann, W.

"ACCURATE NUMERICAL SIMULATIONS OF VORTEX FLOWS. II: INTERACTION OF SWIRLING VORTEX RINGS"

Computers and Fluids, Vol. 41, 2011, pp. 110-118.

An accurate numerical method is applied to the investigation of the flow generated by two co-rotating vortex rings with axial flow in opposite direction at the Reynolds number $Re = 2000$. The rings are shown to generate a strong wake with significant axial vorticity due to the stretching induced by the rings. The rings merge and form a single ring with complex internal structure.

Kolomenskiy, D. and Paoli, R.

"NUMERICAL SIMULATION OF THE WAKE OF AN AIRLINER"

Journal of Aircraft, Vol. 55, No. 4, July-August 2018, pp. 1689-1699.

Large-eddy simulation of the wake past a realistic model airliner at cruise is presented. The near wake is resolved in a rectangular domain that extends through a distance of 3.33 times the wing span downstream from the wing tips. Dynamical properties of the trailing vortices and the jets are analyzed. The Moore-Saffman model is found consistent with the tangential velocity profiles obtained from the

numerical simulation. Recommendations are made for the future far-wake modeling using the near-wake data as the initial condition.

Kolomenskiy, D., Paoli, R. and Boussuge, J.-F.

"HYBRID RANS-LES SIMULATION OF WINGTIP VORTEX DYNAMICS"

Proceedings of the ASME 2014 4th Joint US-European Fluids Engineering Division Summer Meeting (FEDSM2014), August 2014, Chicago, IL.

This paper presents a feasibility study of a hybrid RANS-LES approach to numerical simulation of aircraft wing-tip vortices. A NACA 0012 wing is considered for which earlier published experimental and numerical data are available. Mesh sensitivity tests of our RANS solver and comparisons between two different turbulence models indicate that the RANS approach adequately describes the flow upstream from the trailing edge, but overestimates the rate of decay of the wing-tip vortex. A hybrid RANS-LES method is presented that results in a better agreement with the wind tunnel experiment, hence this approach is suggested for numerical simulation of the wake of an airliner.

Kolos-Lakatos, T.

"A SYSTEM LEVEL STUDY OF NEW WAKE TURBULENCE SEPARATION CONCEPTS AND THEIR IMPACT ON AIRPORT CAPACITY"

PhD Thesis, June 2017, Massachusetts Institute of Technology, Cambridge MA.

The air transportation industry continues to grow worldwide, but demand is often limited by available airspace and airport capacity. This thesis focuses on evaluating new air traffic procedures: specifically, new, and emerging wake turbulence separation rules that could potentially increase runway capacity based on today's knowledge of wake vortex turbulence and technological capabilities. While legacy wake separation rules establish aircraft-classes based on weight of aircraft, these new separation rules can define separation standards by considering other aircraft parameters and dynamic wind conditions. A fast-time runway system model is developed for studying these wake separation rules, using Monte-Carlo simulations, to provide accurate and realistic runway capacity estimates based on the randomness of arrival and departure operations. A total of nine new proposed wake separation rules are analyzed in detail, which include both distance-based and time-based methods, as well as static and dynamic concepts. Seven of the busiest and most delayed U.S. airports are selected as case studies for the illustration of runway capacity benefits enabled by these new wake separation rules: Boston (BOS), New York J.F. Kennedy (JFK), New York LaGuardia (LGA), Newark (EWR), San Francisco (SFO), Los Angeles (LAX), and Chicago O'Hare (ORD). For a detailed capacity analysis, the new wake separation rules are tested under the most constraining runway configurations at each of these airports. The results indicate that increasing the number of aircraft wake categories can increase runway capacity, but the added benefits become smaller with each new category added. A five-or six-category wake separation system can capture most of the runway capacity that can be achieved with a static pair-wise system. Additionally, shifting wake category boundaries between airports as a function of local fleet mix

can provide additional runway capacity benefits, meaning that airport specific wake separation rules can increase capacity over a universal separation rule system. Among the new wake separation rules, the results indicate that reducing wake separations further from current minimum separations (separation values of 2NM or less) can shift the operational bottleneck from the approach path to the runway, as runway occupancy time becomes the limiting factor for inter-arrival separations. The findings from the time-based separation rule demonstrate that switching from distance-based separations to time-based separations in strong headwind conditions can recover significant lost capacity. Time-based separation rules can be of great value to increase operational reliability and capacity predictability at airports in all weather conditions. Moreover, the results also indicate that a reduction in minimum separations enabled by dynamic wind and aircraft information can offer marginal runway capacity benefits over the capacity enabled by static pair-wise wake separations, as more and more aircraft pairs become limited by runway occupancy time. Therefore, a joint effort is needed for reducing both wake separations and runway occupancy to accommodate future air traffic demand.

Kolos-Lakatos, T.

"THE INFLUENCE OF RUNWAY OCCUPANCY TIME AND WAKE VORTEX SEPARATION REQUIREMENTS ON RUNWAY THROUGHPUT"

MS Thesis, May 2013, MIT, Cambridge, MA.

Air traffic growth in the U.S. has led to runway capacity constraints in the air transportation network. There has been limited new construction of runways due to land availability. One approach to increase capacity of existing runways is to reduce inter-arrival separations during the final approach phase of flight. This study evaluates two major elements influencing runway capacity; runway occupancy and wake vortex separation, and under what conditions each becomes a constraint to runway capacity. A detailed analysis of runway occupancy time measurements and wake vortex separation measurements is performed for Boston, Philadelphia, New York La Guardia, and Newark airports based on Airport Surface Detection Equipment Model-X (ASDE-X) aircraft surveillance data. The findings of this study indicate that runway occupancy does not necessarily scale with aircraft size. Small aircraft often occupy the runway as often as large aircraft, which limits the potential for reduced separations behind small aircraft. The results also indicate that high-speed runway exits can make a significant difference in runway occupancy. Runways equipped with high-speed exits have lower runway occupancy times than runways equipped with standard 90-degree exits. Comparison of runway occupancy times in Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) suggest no significant difference between the two weather conditions. Wake vortex separation measurements show that aircraft pairs with small lead aircraft receive longer separation buffers than other aircraft pairs, and airports with more runways implement longer separation buffers. The comparison of landing time intervals and runway occupancy illustrates that wake vortex separation requirements limit runway capacity when heavy or Boeing 757 is the lead aircraft. Lastly, this study evaluates the runway capacity benefits of reduced wake separation requirements for the aircraft re-categorization (RECAT) program. The results estimate an 8.2-8.3% increase in runway capacity at Philadelphia and at Newark, a 7.8%

increase at Boston, and a 5.1% increase at La Guardia. The magnitude of benefits strongly depends on how the local traffic mix looks like.

Kolos-Lakatos, T. and Hansman, R. J.

"THE INFLUENCE OF RUNWAY OCCUPANCY TIME AND WAKE VORTEX SEPARATION REQUIREMENTS ON RUNWAY THROUGHPUT"

Report ICAT-2013-08, August 2013, MIT International Center for Air Transportation, Cambridge MA.

Air traffic growth in the U.S. has led to runway capacity constraints in the air transportation network. There has been limited new construction of runways due to land availability. One approach to increase capacity of existing runways is to reduce inter-arrival separations during the final approach phase of flight. This study evaluates two major elements influencing runway capacity; runway occupancy and wake vortex separation, and under what conditions each becomes a constraint to runway capacity. A detailed analysis of runway occupancy time measurements and wake vortex separation measurements is performed for Boston, Philadelphia, New York La Guardia, and Newark airports based on Airport Surface Detection Equipment Model-X (ASDE-X) aircraft surveillance data. The findings of this study indicate that runway occupancy does not necessarily scale with aircraft size. Small aircraft often occupy the runway as long as large aircraft, which limits the potential for reduced separations behind small aircraft. The results also indicate that high-speed runway exits can make a significant difference in runway occupancy. Runways equipped with high-speed exits have lower runway occupancy times than runways equipped with standard 90-degree exits. Comparison of runway occupancy times in Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) suggest no significant difference between the two weather conditions. Wake vortex separation measurements show that aircraft pairs with small lead aircraft receive longer separation buffers than other aircraft pairs, and airports with more runways implement longer separation buffers. The comparison of landing time intervals and runway occupancy illustrates that wake vortex separation requirements limit runway capacity when heavy or Boeing 757 is the lead aircraft. Lastly, this study evaluates the runway capacity benefits of reduced wake separation requirements for the aircraft re-categorization (RECAT) program. The results estimate an 8.2-8.3% increase in runway capacity at Philadelphia and at Newark, a 7.8% increase at Boston, and a 5.1% increase at La Guardia. The magnitude of benefits strongly depends on how the local traffic mix looks like.

Kolos-Lakatos, T. and Hansman, R. J.

"A SYSTEM LEVEL STUDY OF NEW WAKE TURBULENCE SEPARATION CONCEPTS AND THEIR IMPACT ON AIRPORT CAPACITY"

Report ICAT-2017-03, April 2017, MIT International Center for Air Transportation, Cambridge, MA.

The air transportation industry continues to grow worldwide, but demand is often limited by available airspace and airport capacity. This thesis focuses on evaluating new air traffic procedures: specifically, new and emerging wake turbulence separation rules that could potentially increase runway capacity

based on today's knowledge of wake vortex turbulence and technological capabilities. While legacy wake separation rules establish aircraft-classes based on weight of aircraft, these new separation rules can define separation standards by considering other aircraft parameters and dynamic wind conditions. A fast-time runway system model is developed for studying these wake separation rules, using Monte-Carlo simulations, to provide accurate and realistic runway capacity estimates based on the randomness of arrival and departure operations. A total of nine new proposed wake separation rules are analyzed in detail, which include both distance-based and time-based methods, as well as static and dynamic concepts. Seven of the busiest and most delayed U.S. airports are selected as case studies for the illustration of runway capacity benefits enabled by these new wake separation rules: Boston (BOS), New York J.F. Kennedy (JFK), New York LaGuardia (LGA), Newark (EWR), San Francisco (SFO), Los Angeles (LAX), and Chicago O'Hare (ORD). For a detailed capacity analysis, the new wake separation rules are tested under the most constraining runway configurations at each of these airports. The results indicate that increasing the number of aircraft wake categories can increase runway capacity, but the added benefits become smaller with each new category added. A five-or six-category wake separation system can capture most of the runway capacity that can be achieved with a static pair-wise system. Additionally, shifting wake category boundaries between airports as a function of local fleet mix can provide additional runway capacity benefits, meaning that airport specific wake separation rules can increase capacity over a universal separation rule system. Among the new wake separation rules, the results indicate that reducing wake separations further from current minimum separations (separation values of 2NM or less) can shift the operational bottleneck from the approach path to the runway, as runway occupancy time becomes the limiting factor for inter-arrival separations. The findings from the time-based separation rule demonstrate that switching from distance-based separations to time-based separations in strong headwind conditions can recover significant lost capacity. Time-based separation rules can be of great value to increase operational reliability and capacity predictability at airports in all weather conditions. Moreover, the results also indicate that a reduction in minimum separations enabled by dynamic wind and aircraft information can offer marginal runway capacity benefits over the capacity enabled by static pair-wise wake separations, as more and more aircraft pairs become limited by runway occupancy time. Therefore, a joint effort is needed for reducing both wake separations and runway occupancy to accommodate future air traffic demand.

Komatsubara, T. and Kaku, N.

"THE STATUS OF WAKE VORTEX RESEARCH IN JAPAN"

13th CLRC Proceedings, Oct. 2005, Tokyo, Japan, pp. 140-143

Electronic Navigation Research Institute (ENRI) has been researching wake vortex at the aim of effective flight operation since FY2002. We first detected wake vortices generated by medium commercial aircraft (B767) using wind profile LIDAR in FY2002. Based on the result, we newly made LIDAR for the wake vortex observation and has started observation last winter. The LIDAR is set up at our branch site adjacent to Sendai Airport. At the airport 100 commercial aircraft take off/land a day. Most of them belong to category M. This time, we report the activity status of wake vortex research in Japan, and show some observation results of the wake vortices generated by the commercial aircraft.

Komerath, N.

"EXPERIMENTAL RESULTS ON ROTOR WAKES"

ARO Rotorcraft Wake Prediction Basic Research Workshop, March 2009, Georgia Institute of Technology, Atlanta, GA.

The wake of a rotor is at once an extremely complex flow field, and one where the dominant phenomena are amenable to simple description. While the Landgreb-Gray deconstruction of the hover wake structure into tip vortices and helical vortex sheets, done in the early 1960s, still holds mostly true, several other details and implications have been proven. The transition from the near wake to far wake is known to occur through deterministic vortex-pairing rather than through chaotic processes, even at high Reynolds number. Similarly, mysterious 'jitter' phenomena have mostly been shown to be adequately explained through predictable vortex interactions. Through these advances, shown both experimentally and through analysis and computation, it has become possible to calculate rotor wakes to long ages, far beyond the current reach of first-principles finite-difference CFD. Meanwhile, the ancient disconnect between the correct wake geometry as calculated from blade loading, and the correct thrust as calculated using the wake geometry, has been attributed to a basic flaw in the application of lifting-line analysis to rotor wakes. Patient application of accurate non-intrusive measurement techniques in facilities where vortex-wall interactions are minimized, have enabled clean measurements of vortex core structure in axial and in edgewise flight, to large wake ages. This has enabled a new look at the data in the literature. The traditional assumption that all the vorticity outboard of the bound circulation peak will roll into the tip vortex, has been debunked by experiments, and by correlation of data from a broad range of experiments done in several organizations over the years. It is seen that a large part of this vorticity gets convected into the edge of the inboard vortex sheet. The extent to which this occurs depends on the details of the blade tip shape, demanding high-resolution numerical techniques to capture in predictive analysis.

Komerath, N. and Smith, M. J.

"ROTORCRAFT WAKE MODELING: PAST, PRESENT AND FUTURE"

Proceedings of the European Rotorcraft Forum, Sept. 2009, Hamburg, Germany.

Rotorcraft wake modeling is still a major concern in rotorcraft design and analysis as it influences the aerodynamic, aero-acoustic, and aeroelastic behavior of the vehicle. This paper presents a comprehensive overview of rotorcraft wake modeling, in the last decade, from the experimental, theoretical and computational viewpoints. Present capabilities are discussed and trends for future development are explored based on a recent Army Research Office sponsored Workshop in Wake Modeling held in March 2009 at the Georgia Institute of Technology, in which experts from all over the globe discussed status and limitations, as well as future needs and trends in wake modeling. This paper summarizes this workshop and juxtaposes it with current research on-going in wake experimentation and numerical modeling. Advances in computational fluid dynamics have improved near- and mid-wake modeling capabilities, but hybrid methods that employ vortex element, vorticity transport or vorticity

confinement methods will be necessary for long-age (far-wake) modeling in the near-term. A new hover experiment with high-accuracy measurements that tie the blade loading, rotor performance and wake characteristics is needed for the numerical model correlation and development.

Komerath, N. M. and Tung, C., editors

"PROCEEDINGS OF THE ARO ROTORCRAFT WAKE PREDICTION BASIC RESEARCH WORKSHOP"

Proceedings of the ARO Rotorcraft Wake Prediction Basic Research Workshop, March 2009, Georgia Institute of Technology, Atlanta, GA.

The structure and dynamics of the wakes from rotor blades continue to pose first-order uncertainties in the prediction of hover payload and forward flight speed of rotorcraft. The structure of the rotor wake continues to pose challenges in prediction and measurement. There have been advances in the theory, computational approaches, visualization, and measurement capabilities in this field in the past decade, but these have been slow to be translated into first-principles based prediction capability for vehicle design and analysis.

Komerath, N. M., Smith, M. J. and Tung, C.

"A REVIEW OF ROTOR WAKE PHYSICS AND MODELING"

Journal of the American Helicopter Society, Vol. 56, No. 2, Issue 1, April 2011, pp. 22006-1 to 22006-19.

This paper presents an overview of developments in rotorcraft wake modeling, particularly in the past decade, from the experimental, theoretical, and computational viewpoints. Current understanding of wake physics and limitations in wake modeling are summarized and juxtaposed with trends experimental and numerical research. Advances in flow imaging and velocimetry have provided evidence that supports simplified models of rotor wake behavior. Persistence of tip vortices to long ages, deterministic rollup phenomena leading to the transition to the far wake, and entrainment of a part of the nascent tip vortex vorticity into the counterrotating inboard wake have been shown through experiments. Advances in computational fluid dynamics have improved near- and far-wake wake modeling capabilities. Hybrid methods that employ vortex element, vorticity transport, or vorticity confinement methods will be necessary for long-age (far-wake) modeling soon. A new hover experiment with high-accuracy measurements that tie the blade loading, rotor performance, and wake characteristics is one suggestion to facilitate numerical model correlation and development.

Komerath, N. M., Thompson, T. L., Kwon, O. J. and Gray, R. B.

"VELOCITY FIELD OF A LIFTING ROTOR BLADE IN HOVER"

J. Aircraft, Vol. 25, No. 3, March 1988, pp. 250-257

Detailed measurements have been made using a laser velocimeter in the close vicinity of a lifting, single-bladed model rotor blade in simulated hover conditions to validate codes for predicting

rotorcraft aerodynamics. Data acquired at a rotor tip speed of 32 m/s and a tip Reynolds number of $2.7 \times 100,000$ are compared with predictions made using a thick-bladed panel code coupled to a prescribed wake calculation. Rotor inflow measurements are seen to agree closely with panel code results, even when examined with high chordwise resolution. Agreement is less definite in the near wake, where strong tip vortex effects are felt, and the vortex core model becomes important. Tip vortex formation is clearly visible from the data. Deviations from periodicity are insignificant in the close vicinity of the blade. Particle spin-out effects are seen to be pronounced in the vortex core when using conventional seeding materials but to be greatly reduced using incense seeding. The precise measurement of vortex core velocity profiles is seen to be within reach.

Komerath, N., Wong, O. and Ganesh, B.

"ON THE FORMATION AND DECAY OF ROTOR BLADE TIP VORTICES"

AIAA Paper No. 2004-2431, Portland, OR, June 2004

Models for the rate of decay of rotor tip vortices, based on near-wake data and computations, disagree with the observed persistence of rotor tip vortices for many revolutions. A correlation of data from the literature shows that the measured tip vortex strength is only 40% of the strength expected from the peak of the blade bound circulation, for blades with sharply-cut straight-edged tips, over a wide range of tip Mach and Reynolds numbers. Explanations of this drop in the near wake through turbulence models, are seen to be both counter-intuitive and in conflict with measurements of turbulent fluctuations. Using flow visualization and velocimetry in the wake of a 2-bladed rotor in low-speed forward flight, explanations are shown for these mysteries. Shear layer development at the blade tip, and the twist distribution of the blade have a strong influence on the fraction of the blade tip vorticity lost into the inboard counter-rotating wake. The observations of elliptic core shape and of multiple local extrema of axial velocity deficit, are shown to be features of the shear-layer separation and rollup processes. Blade-to-blade differences in vortex evolution from the same rotor are traced to surface texture differences at the blade tip. Results in the literature reporting 90 to 100% tip circulation recovery for such blades, are seen to be in cases where the induced velocity due to the tip vortex could not be distinguished from that due to the inboard sheet.

Kompenhans, J., Dieterle, L., Raffel, M., Monnier, J.-C., Gilliot, A., De Gregorio, F. and Pengel, K.

"PARTICLE IMAGE VELOCIMETRY: STATUS OF DEVELOPMENT AND EXAMPLES OF APPLICATION IN INDUSTRIAL TEST FACILITIES"

Proceedings 3rd ONERA-DLR Aerospace Symposium, Paris, France, June 2001, pp. S4-1/1-12

For the past few years particle image velocimetry (PIV) has been increasingly used for aerodynamic research and development. This is mainly due to the unique feature of the PIV technique, which allows the recording of a complete velocity field in a plane of the flow within a few microseconds. Thus, PIV provides information about unsteady flow fields, which is difficult to obtain with other experimental techniques. The short acquisition time and fast availability of data reduce the operational time, and

hence cost, in large scale test facilities. Technical progress made in the last years allowed the PIV teams of the European research establishments on aeronautics to develop reliable, modular PIV systems for use in industrial wind tunnels. Development, and application of PIV as well as information exchange about PIV with industrial end-users have been considerably supported by EC. This paper will summarize the state-of-the-art of PIV by describing the basic features of a PIV system for application in wind tunnels and will present some results of recent PIV applications within EC funded projects such as EUROPIV 1 and 2, PivNet, APIAN, WAVENC, EUROWAKE, C-Wake, EUROLIFT, and HELIFLOW. Most of these results have been obtained by joint teams of different EREA members, European aeronautical industry, and wind tunnels.

Kompenhans, J., Dieterle, L., Vollmers, H., Stuff, R., Schneider, G., Dewhirst, T., Raffel, M., Kaehler, C., Monnier, J. C. and Pengel, K.

"AIRCRAFT WAKE VORTEX INVESTIGATIONS BY MEANS OF PARTICLE IMAGE VELOCIMETRY - MEASUREMENT TECHNIQUE AND ANALYSIS METHODS"

Proceedings of 3rd Int'l. Workshop on PIV'99, University of California, Santa Barbara, CA, 1999, pp. 255-260

The investigation of wake vortices is a traditional subject of aerodynamics. A continuous interest arises from general safety aspects of aircraft whereas in the past years the need to reduce the safety distance between following aircraft stimulated new investigations. This paper summarizes experimental aspects of work carried out in this field employing modern optical techniques for the measurement of instantaneous flow velocity fields. It will be shown that the use of a modern mobile Particle Image Velocimetry (PIV) system in combination with advanced evaluation and post processing techniques allows much faster progress in such a complex field of high technological (and economical) interest.

Kompenhans, J., Dieterle, L., Vollmers, H., Stuff, R., Schneider, G., Raffel, M., Dewhirst, T., Kahler, C., Pengel, K., Monnier, J.-C., Gilliot, A. and Coton, P.

"QUALITATIVE AND QUANTITATIVE VISUALIZATION OF WAKE VORTICES IN INDUSTRIAL TEST FACILITIES"

Proceedings of 9th International Symposium on Flow Visualization, Edinburgh, Scotland, August 2000, pp. 437-1 - 437-10.

The investigation of wake vortices is a traditional subject of aerodynamics. A continuous interest arises from general safety aspects of aircraft, which became even more important after the recent announcement of aircraft manufacturers in Europe and the US to bring larger airplanes into operation during the next few years. A number of national and international projects have been performed in Europe in the past years comprising experimental as well as theoretical investigations of the wake vortex problem. The objective of this paper is to show that the use of a modern mobile particle image velocimetry (PIV) system in combination with advanced evaluation and post processing techniques

allows to improve the insight into the complex flow field of wake vortices as compared to traditional methods such as smoke visualization and five-hole probes.

Kong, J.

"SAFETY EVALUATION OF A380 WAKE TURBULENCE SEPARATION"

Applied Mechanics and Materials, Vols. 278-280, 2013, pp. 31-34.

CAAC (Civil Aviation Administration of China) set a standard on A380 wake turbulence separation right after China Southern Airlines brought in Airbus A380 in 2001. This paper considers from the possibility of the latter aircraft wake turbulence influencing the preceding one, which means the wake turbulence risk, makes safety evaluation on the wake turbulence separation standard of the preceding aircraft as A380, and the latter one as heavy type, medium type and light type, based on the safety target level that ICAO (International Civil Aviation Organization) authorized. Each type chooses a typical aircraft to calculate the possibility of influenced by the preceding wake turbulence corresponding with the standard under calm wind. The final result shows that the A380 wake turbulence separation standard setting by CAAC is safe.

Konig, R.

"AIRCRAFT RESPONSE AND PILOT BEHAVIOR DURING A WAKE VORTEX ENCOUNTER PERPENDICULAR TO THE VORTEX AXIS"

AGARD, Flight in Adverse Environmental Conditions, September 1989.

Vortex systems can be hazardous to trailing aircraft which encounter them in flight. The greatest hazard occurs in areas where aircraft from a wide range of classes operate and where the flight paths are close to the ground. Upwash velocities induced by the wake vortices can be equivalent to the design gust velocities. Furthermore, different types of hazardous effects exist when encountering the vortex system, such as imposed rolling and pitching moments, a loss of rate of climb, a loss of altitude and structural loads. Aircraft response and pilot behavior during takeoff are described when a wake vortex is encountered perpendicular to the vortex axis. The aircraft response is calculated by nonlinear digital simulation with a mathematical model of a wake vortex system close to the ground. This real-time vortex model is also used in the Boeing B-737 simulator of Deutsche Lufthansa in order to examine the pilot behavior. Close to the ground, the wake vortex system induces additional horizontal velocities. There exists a critical flight path where very large g-loads are induced by vertical and horizontal vortex velocities and normal vertical acceleration shortly after takeoff. Often the pilot will attempt to counteract these g-loads, but this produces only a small effect.

Konopka, J.

"WIND PROFILES AND THEIR IMPACT ON WAKE TURBULENCE SEPARATION - FIRST RESULTS FROM THE WAKE VORTEX WARNING SYSTEM AT FRANKFURT AIRPORT"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

The Wake Vortex Warning System, WVWS, at Frankfurt Airport in particular the so-called glide-path extension is now technically completed. The glide-path extension shall enable a reduction of the wake turbulence separation using predictions of the wake vortices' motion between the two closely spaced parallel final approach paths for runways 25L and 25R in the entire height range up to 5000 ft above ground level. The glide-path extension of the WVWS comprises a Wind-Temperature-Radar with a Radio Acoustic Sounding System for high-resolution measurements of wind and temperature profiles in real time. Every two minutes the actual wind profile is measured and fed into a wind forecast algorithm which produces estimates of the wind up to 20 minutes ahead. This information is then used to determine whether wake transport between the two neighboring glide-paths can be excluded with high confidence. The installation is now running on a routine basis since May 2004 without any modification to the separation standards yet. The data collected under operational conditions so far allows for a first assessment of the potential capacity increase when such a crosswind-based system is used for approaches to closely spaced parallel runways. In the presentation the impact of different factors on the estimated benefit in terms of capacity will be discussed. These influencing factors include for example the wind profile itself, the runway geometry and the performance of aircraft on the glide-slope. The paramount system requirements regarding data availability and accuracy are confronted with the experience gathered so far. It turns out that the meteorology deteriorates the benefits for two reasons: Firstly, the state of the atmosphere does not always allow for safe reduction of the wake turbulence separation and secondly the performance of remote sensing systems like wind-profilers, sodars or lidars, etc. are crucially dependent on the ambient conditions.

Konopka, J.

"INCREASING CAPACITY BY WAKE TURBULENCE AVOIDANCE SYSTEMS AT FRANKFURT/MAIN AIRPORT"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Frankfurt/Main is among the 10 largest airports in the world. It accommodates a traffic volume of 460,000 movements per year (2000) including a 30% fraction of heavy type aircraft like Airbus 340s or Boeing 747s. The runway system consists of two closely spaced parallel runways (25/07) plus a third runway (18) that is exclusively used for departures. One of the most stringent capacity-limiting factors are wake turbulence separation requirements due to leading heavy aircraft. German Air Navigation Services (DFS) together with Frankfurt Airport (FRAPORT) is developing systems and novel procedures that allow for safe reduction of wake turbulence separation minima for landing traffic on different but close spaced runways even in IMC conditions. This paper gives an overview on the concept of the Wake Vortex Warning System (WVWS), its components, and how the system will be incorporated in a real Air Traffic Control environment. While current ICAO provisions rely on wake decay, the novel procedure will ensure wake turbulence safety because the wake of the leading (heavy type) aircraft will be transported away from the flight corridor of the trailing (medium type) aircraft. This shall be accomplished by accurate measurement of the prevailing meteorological conditions and subsequent forecast of the wake vortices' motion between the two glideslopes. Currently the WVWS covers a

safety box of 80 m height, however as a next step a wind-temperature radar will supplement the system and provide necessary data to extend the prognosis along the entire final approach path. Another alternative is presently tested in field trials: In the High Approach Landing System/Dual Threshold Operation (HALS/DTOP) project, FRAPORT and DFS have built an additional threshold (26L) on an existing runway (25L). The new threshold is displaced by 1500 m and thus ensures that aircraft approaching 26L will always stay 80 m above leading aircraft on 25R. Due to this 80 m shift the aircraft's flight corridor will be clear of wake turbulence.

Konopka, J. and Fischer, H.

"EDDF-2 DATA COLLECTION CAMPAIGN REPORT"

CREDOS Report D2-4, May 2008, DFS Deutsche Flugsicherung GmbH, Langen, Germany.

Operational surveillance and meteorological data have been collected at Frankfurt airport. The EDDF-2 data collection campaign lasted for more than one year to characterize the true operating conditions at a location where wake turbulence separation minima limit air traffic capacity. For six months also wake vortex data of departing aircraft have been collected and correlated to the other data. This report describes how the EDDF-2 data collection campaign was organized, summarizes its characteristic features of and provides information about its overall performance. Results of statistical analyses of various subsets of the data are given.

Konopka, J. and Fischer, H.

"THE WAKE VORTEX WARNING SYSTEM AT FRANKFORT AIRPORT"

24th Digital Avionics Systems Conference, Vol. 1, Nov. 2005, pp. 3.A.6-1-3.A.6-14

The Wake Vortex Warning System, WVWS, at Frankfurt Airport, in particular the so-called glide-path extension is now technically completed. The system shall enable a reduction of the wake turbulence separation using predictions of the wake vortices' motion between the two closely spaced parallel final approach paths for runways 25L and 25R up to 5000 ft above ground level. The glide-path extension of the WVWS comprises a wind-temperature radar with a radio acoustic sounding system, WTR/RASS for real-time measurements of wind and temperature profiles. Every two minutes the wind profile is measured and fed into a wind forecast algorithm which produces estimates of the wind up to 20 minutes ahead. This information is used to determine whether wake transport between the two neighboring glide paths can be excluded with high confidence. The installation is now running on a routine basis since May 2004 without any modification to the separation standards yet. The data collected under operational conditions so far allows for a first assessment of the potential capacity increase when such a crosswind-based system is used for approaches to closely spaced parallel runways. The impact of different factors on the estimated benefit in terms of capacity will be discussed. These influencing factors include for example the wing profile itself, the runway geometry, and the performance of the aircraft on the glide slope. The paramount system requirements regarding data availability and accuracy are confronted with the experience gathered so far. It turns out that the

meteorology deteriorates the benefits for two reasons: Firstly, the state of the atmosphere does not always allow for safe reduction of the wake turbulence separation and secondly the performance of remote sensing systems like wind profilers, sodars or lidars etc. are crucially dependent on the ambient conditions.

Konopka, J. and Fisher, H.

"THE CREDOS REPORT: EDDF-2 DATA COLLECTION CAMPAIGN REPORT"

D2-4, November 2009.

Operational surveillance and meteorological data have been collected at Frankfurt airport. The EDDF-2 data collection campaign lasted for more than one year to characterize the true operating conditions at a location where wake turbulence separation minima limit air traffic capacity. For six months also wake vortex data of departing aircraft have been collected and correlated to the other data. This report describes how the EDDF-2 data collection campaign was organized, summarizes its characteristic features of and provides information about its overall performance. Results of statistical analyses of various subsets of the data are given.

Konopka, J. and Fisher, H.

"THE CREDOS PROJECT: EDDF 6-MONTH WAKE AND WEATHER DATASET RWY25L/R [EDDF-2]"

D1-2, November 2009.

A long-term measurement campaign of vortices from departing aircraft has been conducted at Frankfurt airport between January and June 2007. Meteorological as well as aircraft trajectory data have been collected in parallel. Data from the various sensors have been fused and correlated to characterize the vortices in an operational and meteorological context. More than 10,000 cases mostly including heavy aircraft taking off runway 25R have been collected. The data is delivered on a separate data carrier. This document describes the different formats of the collected data, summarizes the definitions, and gives additional guidance for further analyses.

Konopka, J. and Hallock, J. N.

"NEAR GROUND LATERAL TRANSPORT/DECAY OF VORTICES AS OBSERVED FROM WINDLINE DATA AT FRANKFURT AND ITS IMPLICATIONS"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

The Frankfurt windline is used to track vortices under routine operations at Frankfurt/Main Airport. Ten state-of-the-art ultrasonic anemometers are installed between the closely spaced parallel approach paths to runways 25L and 25R approximately 0.5 NM before the thresholds. The device is part of the Wake Vortex Warning System and is operating on a 24-hours a day, 365 days a year basis. Although the

system has not been designed for this purpose and therefore has some limitations, it allows for wake vortex behavior analyses to an extent that cannot be achieved with data dedicated short-term measurement campaigns. Major advantages of the Frankfurt Windline data are: a high statistical significance, even if the data is sorted by aircraft types; a large fraction of heavy aircraft; and measurement under all weather conditions. In the presentation the influence of the ambient meteorological conditions on wake transport and decay is examined: The vortex transport distances are well correlated with the ambient crosswind, but a clear relationship between the lifetime of wake vortices and any of the available atmospheric variables could not be determined. Nevertheless, the data suggests that wake vortex lifetimes near the ground increase with aircraft size in such a way that is not in agreement with the widely used scaling with normalized time.

Konopka, J., Rudolph, R. and Schmid, H.-P.

"THE GERMAN WAKE VORTEX PROJECT FOR FRANKFURT AIRPORT PARALLEL RUNWAY SYSTEM 25"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Quebec, Canada, December 1997, pp. 27-32

DFS has designed a Wake Vortex Warning System for Frankfurt/Main Airport. The system is safe and operational but faces acceptance problems from the side of the users. This paper outlines the basic principles and the present status of the German WVWS project. It includes a cost/benefit analysis, identifies the present problems, and gives an outlook on how the still existing problems may be brought to a solution.

Konrath, R. and von Carmer, C. F.

"TOWING TANK INVESTIGATIONS ON 2- AND 4-VORTEX SYSTEMS IN GROUND EFFECT USING PIV"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

The spatial-temporal flow evolution of 2- and 4-vortex systems in ground proximity was investigated performing flow velocity field measurements in a tow tank. The F13 model consisting of one or two rectangular wings is used as vortex generator and is towed along an adjustable ground plate at specific heights of $h/b = 0.5, 0.25$ and 0.125 with respect to the trailing edge of the main wing. Three different vortex configurations were investigated; i.e. a 2-vortex system and two 4-vortex systems consisting of two co- and counter-rotating vortex pairs with a span width ratio of 0.3 and circulation ratios of plus and minus 0.3 . A Stereo Particle Image Velocimetry setup is employed to determine the flow velocity fields in a cross plane. The flow fields are analyzed with respect to flow separation at the ground, the generation of secondary vortices and the spatial-temporal development of the vortex trajectories and their circulation strengths.

Konrath, R. and von Carmer, C. F.

"VALIDATION EXPERIMENT WITH 4-VORTEX WAKE IN LARGE TOW TANK"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

Stereo PIV measurements on a 2- and 4-vortex system have been performed in a large tow tank of SVA at Potsdam. The aim was to provide experimental data for validation of numerical simulations of 4-vortex systems with respect to medium- and long-wave instabilities. Such instabilities could be an efficient way to promote a decay of the wing tip vortices. The experiments had to be performed within a large facility to preclude flow disturbances caused by end- and wall-effects. The considered 4-vortex system consists of two counter-rotating vortex pairs with a span width ratio of 0.3 and a circulation ratio of -0.3. For comparisons also the corresponding 2-vortex system is measured. Using DLR's generic wing model F-13 of 0.3 m span width as vortex generator the large tow tank of SVA at Potsdam allows measurements at very far distances which can be expressed by the dimensionless vortex age parameter of 8. A submersible Stereo PIV system was attached to a vertical traversing system to determine cross-sectional velocity fields of the descending wake vortex system. Specific time dependent triggering sequences account for the occurring high ranges of flow velocity magnitudes. The port as well as the starboard side vortices are measured simultaneously using a large observation area. The measurement's setup is described and first results will be discussed qualitatively.

Konrath, R., Agocs, J., Otter, D., Roosenboom, E. W. M., Wolf, Th. and Quest, J.

"FLOW FIELD MEASUREMENTS BY PIV AT HIGH REYNOLDS NUMBERS"

AIAA Paper 2013-0869, January 2013, Grapevine, TX.

Stereo PIV measurements have been applied to the wake flow on a high-lift aircraft configuration in the cryogenic pressurized transonic wind tunnel ETW at realistic Mach and Reynolds numbers. A cryo-PIV system, developed specially for the ETW to enable flow field measurements at gas temperatures down to 110 K and gas pressures of up to 450 kPa, has been adapted to a large measurement field extending over the complete span width of the half wing model. The specific seeding technique using ice particles and the optical systems are described as well as the automation the PIV measurements linked with the wind tunnel control system. First results of the vortical wing wake flow obtained at a Reynolds number of 17 million will be presented.

Konrath, R., Pallek, D., Mattner, H. and v. Carmer, C. F.

"ANALYSIS OF FLOW FIELD MEASUREMENTS OBTAINED IN A LARGE TOW TANK REGARDING THE DECAY OF WAKE VORTICES IN THE FAR-FIELD FOR TWO- AND FOUR-VORTEX SYSTEMS"

AIAA Paper 2009-0342, Jan. 2009, Orlando, FL

Stereo PIV measurements on a 2- and 4-vortex system have been performed in a large tow tank of SVA in Potsdam. The considered 4-vortex system consists of two counter-rotating vortex pairs generated by wings of a span width ratio of 0.3 and a circulation ratio of -0.3. As reference the

corresponding 2-vortex system is also considered. A submersible Stereo PIV system attached to a vertical traversing system was employed. Cross-plane velocity fields are obtained of the descending wake vortex system to access the vortex dynamics well into the wake far field (x/b greater than 500 and non-dimensional time greater than 11). The spatio-temporal evolution of the vortex systems is analyzed with respect to the vortex trajectories, circulations and core radii as well as the total kinetic energy contained in the measured flow field.

Konstadinopoulos, P., Thrasher, D. F., Mook, D. T., Nayfeh, A. H. and Watson, L.

"A VORTEX-LATTICE METHOD FOR GENERAL, UNSTEADY AERODYNAMICS"

J. Aircraft, Vol. 22, No. 1, January 1985, pp. 43-4.

A general method of calculating unsteady, incompressible, inviscid, three-dimensional flows around arbitrary planforms has been developed. The method is an extension of the vortex-lattice technique. It is not limited by aspect ratio, camber, or angle of attack, as long as vortex breakdown does not occur above the surface of the wing and separation occurs only along sharp edges. As the wing performs arbitrary maneuvers, the position of the wake and the distribution of circulation on the wing and in the wake are obtained as functions of time. One desirable feature of the present method is its ability to treat steady lifting flows very efficiently. Several examples of steady and unsteady flows are presented. These include rectangular wings, with and without flaps, delta, and cropped delta wings.

Kontis, K.

"EXPERIMENTAL STUDIES ON THE INTERACTION OF JETS WITH THE VORTEX WAKE OF SLENDER BODIES"

Journal of Visualization, Vol. 8, No. 2, 2005, pp. 109-116.

An experimental study has been conducted to examine the low-speed aerodynamic characteristics of a pair of circular jets behavior in the vortex wake of a blunted cone cylinder-body combination with and without a 70-degree leading edge sweep delta wing. The induced flow field was examined via two-dimensional hot-wire anemometry surveys. Comparisons were made between the induced wake with and without the circular jets. The flow field over the models was visualized using smoke and oil visualization. The jet pair was found to undergo severe distortion within a very short distance from the nozzle exits. The shape of the jets was shown to change considerably when placed in the wake flow field of the models, which caused the jet pair to spread and become entrained within the vortices and wake created by the models.

Koochesfahani, M. M.

"VORTICAL PATTERNS IN THE WAKE OF AN OSCILLATING AIRFOIL"

AIAA Journal, Vol. 27, No. 9, September 1989, pp. 1200-1205

The vortical flow patterns in the wake of a NACA 0012 airfoil pitching at small amplitudes are studied in a low-speed water channel. It is shown that a great deal of control can be exercised on the structure of the wake by the control of the frequency, amplitude, and the shape of the oscillation waveform. An important observation in this study is the existence of an axial flow in the cores of the wake vortices. Estimates of the magnitude of the axial flow suggest a linear dependence on the oscillation frequency and amplitude.

Kopiev, V. F. and Chernyshev, S. A.

"LONG-WAVE INSTABILITY OF A VORTEX RING"

Fluid Dynamics, Vol. 30, No. 6, 1995, pp. 864-869.

The instability of barrel-shaped vibrations of a vortex ring in an ideal fluid is investigated. These vibrations, stable for a vortex ring with a piecewise-uniform vorticity profile, appear to be unstable for a vortex ring with a smooth vorticity profile. The instability growth rate is found on the basis of the energy balance equation determining the energy transport from perturbations with negative energy in the critical layer to perturbations with positive energy in the rest of the flow. The curvature of the vortex ring, by virtue of which the perturbations with energies of different signs appear to be connected, plays a prominent role in the mechanism under consideration.

Kopiev, V. F. and Chernyshev, S. A.

"OCTUPOLE RADIATION OF LOCALIZED VORTEX"

AIAA Paper No. 2005-2955, Monterey, CA, May 2005

For a weakly compressible inviscid fluid (with the Mach number $M \ll 1$), we consider the problem of obtaining the maximum possible number of terms of the asymptotic expansion of a sound field in powers of the Mach number for the aerodynamic sound generated by localized vortices. Using Crow's approach and the matching procedure of Van Dyke, quadrupole and octupole terms are obtained in the asymptotic expansion. It is shown that higher moments of the sound field cannot be obtained in such a procedure because of the divergence of the respective integrals in the inner expansion. We discuss the possibility of representing the sound field in terms of expressions for the quadrupole and octupole moments of an incompressible flow with a retarded argument. The theory of vortex ring eigen-oscillations and the formulas for quadrupole and octupole sound obtained previously by the authors based on matching asymptotic expansions are used for predictions of non-axisymmetric octupole radiation generated by eigen-oscillations of the vortex ring. The result obtained previously for axisymmetric case is elaborated for 3D problem. The calculation of octupole term has shown that for thin vortex rings this component depends on the ratio of two small parameters and may appear to be large.

Kopiev, V. F. and Chernyshev, S. A.

"VORTEX RING EIGEN-OSCILLATIONS AS A SOURCE OF SOUND"

J. Fluid Mech., Vol. 341, 1997, pp. 19-57

Two coupled problems are investigated: a complete description of long-wave vortex ring oscillations in an ideal incompressible fluid, and an examination of sound radiation by these oscillations in a weakly compressible fluid. The first part of the paper relates to the problem of eigen-oscillations of a thin vortex ring in an ideal incompressible fluid. The solution of the problem is obtained in the form of an asymptotic expansion in the small parameter μ . The complete set of three-dimensional eigen-oscillations and axisymmetric modes (two-dimensional oscillations) is obtained. It is shown that, unlike the vortex column oscillations which have the form of simple angular harmonics, most of eigen-oscillations of a thin vortex ring have a more complex form which is a combination of two harmonics in the leading approximation. This leads to dramatic changes in the efficiency of sound radiation produced by modes of the vortex ring in comparison with the corresponding modes of the vortex column. In the second part of the paper the solution obtained is used to investigate the process of sound radiation by vortex perturbations in a weakly compressible fluid. The vortex ring eigen-oscillations are classified according to their sound radiation efficiency. It is shown that the modes with the dimensionless frequency about $1/2$ radiate sound most efficiently. They are two isolated modes, two infinite families of Bessel modes and a set of axisymmetric modes.

Koplin, K.

"WAKE VORTICES - A EUROPEAN REGULATORY VIEW"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 3-1 to 3-10

The activities of the 26-member Joint Aviation Authorities (JAA) are described along with JAA's relationship with other European organizations concerned with civil aviation regulations. Wake vortex hazards are worrisome in Europe and must be considered in planning for air traffic growth, but JAA does not consider this an urgent safety problem at present.

Kopp, F.

"THE INFRARED DOPPLER LIDAR: AN IMPORTANT TOOL FOR EXPERIMENTAL INVESTIGATION OF AIRCRAFT WAKE VORTICES"

Optical Society of America, Technical Digest, Vol. 12, 1991, pp. 306-308

The DLR laser Doppler anemometer represents an important contribution to the German wake-vortex program. Especially vortex transport and decay within the area of ground influence have been investigated at Frankfurt Airport.

Kopp, F.

"PROPERTIES OF AIRCRAFT WAKE VORTICES MEASURED BY GROUND-BASED CONTINUOUS-WAVE DOPPLER LIDAR"

Society of Photo-Optical Instrumentation Engineers (SPIE) Proceedings, Vol. 3707, 1999, pp. 204-209

The DLR ground-based cw Doppler lidar has been developed for wind and turbulence measurements in the atmospheric boundary layer. Moreover, it is used for experimental investigations of aircraft wake vortices. This paper presents measurements of wake vortices generated by military-type fixed-wing as well as rotor-wing aircraft. The experimental data are analyzed regarding the structure and circulation of wake vortices and their temporal development. The influence of flight parameters is measured during several consecutive fly-bys. Small variations in the velocity profiles are observed which are overlain by the signatures of the variable wind and turbulence field, a problem which can only be solved by statistical treatment. The influence of the aircraft design is demonstrated by comparison of the vortex signatures generated by two B707-type aircraft with pronounced differences in aircraft design.

Kopp, F.

"DOPPLER LIDAR INVESTIGATION OF WAKE VORTEX TRANSPORT BETWEEN CLOSELY SPACED PARALLEL RUNWAYS"

AIAA Journal, Vol. 32, No. 4, April 1994, pp. 805-810

The paper demonstrates the potential of the Doppler lidar technique for the investigation of aircraft wake vortices. During several extended field experiments at the Frankfurt/Main Airport, the DLR laser Doppler anemometer has measured the vortex properties of a large variety of landing aircraft. These data are used to increase the understanding of the behavior of wake vortices with special emphasis on the horizontal vortex transport in ground effect. In particular, the results of the vortex transport considerations are the basis for air traffic control to enhance the efficiency of closely spaced parallel runway systems with respect to wake vortices.

Kopp, F.

"MORE INSIGHT INTO AIRCRAFT WAKE VORTICES BY MEANS OF GROUND-BASED CW DOPPLER LIDAR"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

Aircraft wake vortices are presenting a potential hazard to other aircraft following closely behind. This is not only a safety problem but also a capacity problem at major airports. Several approaches are under investigation: A reduction of the presently binding separation distances can be achieved by long-range airfield systems or forward-looking onboard sensors for wake vortex detection and warning. In the design phase of new aircraft types, mechanical features for vortex alleviation can be considered. Supposition for these approaches is the precise knowledge of the vortex properties and their temporal behavior. At DLR, a cw Doppler Lidar has been developed for boundary layer wind measurements. This system is also used for the investigation of vortex properties, like velocity distribution, circulation,

transport in ground influence and decay. During several field experiments, the signatures of a large variety of aircraft types have been acquired covering the bandwidth from small business to large commercial aircraft. Experimental data will be presented, including data of scarcely investigated vortices like those being generated by fighter-type aircraft and by helicopters. The relationship to aircraft parameters and to the atmospheric environment will be considered.

Kopp, F.

"EXPERIMENTAL INVESTIGATION OF WAKE VORTEX STRUCTURE AND PROPAGATION USING THE DLR LASER DOPPLER ANEMOMETER"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 46-1 - 46-8

Extensive experiences in the USA and Germany have proved that the infrared Doppler Lidar is the most effective and flexible remote sensing method for wake-vortex detection, measurement, and tracking. Therefore, the DLR Laser Doppler Anemometer has been incorporated into the German Wake Vortex Program. This program is concentrated on the highly frequented Frankfurt Airport where additional capacity limitations are caused by the separation of 1700 ft between the two parallel runways. This separation is often too small for operating both runways independently with respect to wake vortices. Therefore, the main objectives are the determination of the strength and propagation of the vortices of 'new generation' aircraft, such as B757, B767, and A320, and the identification of atmospheric conditions where vortex-independent operation of the parallel runways is possible.

Kopp, F.

"WAKE-VORTEX CHARACTERISTICS OF MILITARY-TYPE AIRCRAFT MEASURED AT AIRPORT OBERPFAFFENHOFEN USING THE DLR LASER DOPPLER ANEMOMETER"

Aerospace Science and Tech., Vol. 3, No. 4, June 1999, pp. 191-199

Experimental investigations of wake vortices generated by military-type aircraft, including fixed-wing and rotary-wing aircraft, were made using the DLR ground-based CW Doppler lidar. Attention was given in the measurements to the vortex roll-up phase. The experimental data analyzed dealt with vortex structure, circulation, and temporal development. Vortex signatures measured during consecutive aircraft flybys were used to investigate the influence of flight parameters, especially the aircraft mass. Small variations in the velocity profiles could be observed, but the differences in flight parameters from flyby to flyby were not large enough to produce systematic variations of the vortex signatures. In practice, the vortex signatures are always overlayed by the signatures of the variable surrounding wind and turbulence field. This problem can be solved on a statistical basis by measuring many cases under the same conditions. The influence of aircraft design was demonstrated by comparing the vortex signatures of two B707-type aircraft showing pronounced design differences, namely a standard B707 and an AWACS E3A, which is a B707 bearing a radome on top of the fuselage. The velocity profiles and, therefore, the circulation profiles of both aircraft show different shapes.

Kopp, F.

"LONG-RANGE DETECTION OF AIRCRAFT WAKE VORTICES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

For flight safety and airport capacity, it is of growing importance to detect wake vortices and atmospheric hazards, like wind shear, downdraft, and clear-air turbulence, well before a possible encounter of the aircraft. This can be achieved either by a forward-looking sensor being installed in the aircraft or by a ground-based sensor covering the approach area of highly-frequented airports. The most promising candidate for such sensors is the Doppler lidar in pulsed version. A pulsed Doppler lidar system has been developed and tested in the frame of the EC Project MFLAME (Multifunction Laser Atmospheric Measuring Equipment). It is based on the laser transceiver unit MAG-1 from CLR Photonics with special features necessary for wake-vortex detection: the pulse repetition rate of 500 Hz allows to cover the field-of-view of 12 x 13 degrees within a few seconds with sufficient spatial resolution and the pulse length of 500 ns provides a range resolution well adapted to the size of the phenomenon. Following the transceiver, the laser beam is twenty-times expanded by an off-axis telescope and then deflected into the sensing area by a scanning device. This device is the combination of two separate units: a fast vertical scanner consisting of two counter-rotating prisms and an oscillating plane mirror providing the horizontal scan. In this way, one complete image is covered within 5 s by a sinusoidal scan pattern with 75 vertical lines. The detector signals from the atmospheric return and the pulse-monitor reference are digitized with 500 MHz sampling rate and stored by the data acquisition and quick-look unit. Links to the scanner device enable the localization of each line-of-sight within the field-of-view. To demonstrate the feasibility of the pulsed lidar for wake-vortex detection, ground tests have been carried out at the airport Toulouse-Blagnac in February and March 2000. There, the lidar system was installed below the glide slope of runway 33L approximately 800 m in front of the threshold. The detection of vortices generated by a large variety of aircraft has been successfully demonstrated up to ranges of more than 2 km.

Kopp, F. and Krichbaumer, W. A.

"EXPERIMENTAL AND THEORETICAL DOPPLER-LIDAR SIGNATURES OF AIRCRAFT WAKE VORTICES"

13th International Laser Radar Conf., NASA Langley, August 1986.

The DFVLR laser Doppler anemometer is a CO₂ continuous wave homodyne system designed for boundary layer wind measurements. During the last three years, it was mainly used in the wake-vortex program at Frankfurt airport for determination of vortex strength, transport, and lifetime. The strategy for that special type of measurement was previously reported in detail along with single experimental results. Therefore, herein is given a short summary of the data concerning questions of air traffic control. In addition to the experimental activities a computer model describing wake-vortex behavior was installed. It allows the comparison of the measured data with the hydrodynamically predicted

quantities. On the other hand, it leads to an improved procedure for future wake-vortex measurements.

Kopp, F., Rahm, S. and Smalikho, I.

"CHARACTERIZATION OF AIRCRAFT WAKE VORTICES BY 2-MICRON PULSED DOPPLER LIDAR"

Journal of Atmospheric and Oceanic Technology, Vol. 21, 2004, pp. 194-206

The 2-micron pulsed Doppler lidar, already successfully used for wind and turbulence measurements, has been modified for long-range wake-vortex characterization. In particular, a four-stage data processing algorithm has been developed to achieve precise profiles of tangential velocities from which the vortex parameters such as trajectories, core separation, tilt angle, and circulation can be derived. The main advantage of the pulsed lidar is its long-range capability of more than 1 km. This allows for observations over long periods from the moment of wake generation to a progressed state of vortex decay. With the field experiment at Tarbes airfield the potential of the 2-micron pulsed Doppler lidar for full-scale wake-vortex characterization has been demonstrated. Two examples showing the parameters of wake vortices generated by large transport aircraft (LTA)-type aircraft will be presented.

Kopp, F., Rahm, S., Smalikho, I., Dolfi, A., Cariou, J.-P., Harris, M. and Young, R. I.

"COMPARISON OF WAKE-VORTEX PARAMETERS MEASURED BY PULSED AND CONTINUOUS-WAVE LIDARS"

Journal of Aircraft, Vol. 42, No. 4, July-August 2005, pp. 916-923

Field trials carried out at Tarbes airfield in the summer of 2002 offered the unique opportunity to compare the results of simultaneous wake-vortex measurements by the pulsed Doppler lidar from DLR, German Aerospace Research Center, and the continuous wave (CW) Doppler lidars from ONERA and QinetiQ. The discrepancies in vortex core position obtained from the data of the pulsed lidar and the CW lidars are 9 m for the vertical and 13 m for the horizontal coordinates. The accuracies of the vortex circulation measurements with the DLR and ONERA lidars are almost the same and equal 13 m squared/s. This accuracy and the long-range capability of the pulsed lidar allows precise measurements over long periods from the moment of wake generation to a progressed state of vortex decay. Moreover, the influence of different atmospheric turbulence conditions and aircraft configurations on the wake-vortex circulation can be analyzed. This has been demonstrated out of ground effect under conditions of weak to moderate levels of turbulence.

Kopp, F., Smalikho, I., Rahm, S., Dolfi, A., Cariou, J.-P., Harris, M., Young, R. I., Weekes, K. and Gordon, N.

"CHARACTERIZATION OF AIRCRAFT WAKE VORTICES BY MULTIPLE-LIDAR TRIANGULATION"

AIAA Journal, Vol. 41, No. 6, June 2003, pp. 1081-1088

Three continuous-wave lidar systems have been deployed to measure simultaneously the airflow associated with wake vortices generated by a medium-size full-scale test aircraft. The lidar systems were positioned to permit investigation of fundamental aspects of vortex behavior. Two lidars were located 27 m apart, along a line parallel to the glide slope. This allowed a consistency check via comparison of the two sets of results and gave an indication of axial variations in vortex location and character. The third lidar was positioned 80 m away along a line perpendicular to the glide slope. This permitted accurate location of the vortex cores by triangulation methods via a tracking algorithm based on an extended Kalman filter, typically to an accuracy of better than plus/minus 4.0 m. The mean value of core separation for a vortex age of 2 s agrees to within 5% of that predicted for this aircraft using the approximation of elliptically distributed lift. Calculation of vortex circulation requires accurate information on vortex range in conjunction with tangent velocity profiles: The trajectories thus determined are an essential input, and, hence, this method will reduce the uncertainty in the values of circulation in comparison to studies involving only a single lidar.

Koppitz, P., Kuerten, J. and Holzaepfel, F.

"THRUST MODELS BASED ON OPERATIONAL FLIGHT DATA USED IN PARAMETER ESTIMATION FOR SAFETY ANALYSES"

31st Congress of the International Council of the Aeronautical Sciences (ICAS 2018), September 2018, Belo Horizonte, Brazil.

Based on available operational flight data of a Boeing 737-300 with CFM56-3 engines, four different thrust models are developed in MATLAB. The model development is supported by the software GasTurb which can compute operating lines for engine components based on a design point. The results are used for the generation of lookup tables. The computed thrust is then utilized in parameter estimation for the landing phase from touchdown to a calibrated airspeed of 50 kts. Here, zero drag coefficients, spoiler drag coefficients and a braking coefficient are estimated for about 1500 flights using the Output Error Method combined with the Gauss-Newton algorithm.

Korkischko, I. and Konrath, R.

"FORMATION FLIGHT OF LOW-ASPECT-RATIO WINGS AT LOW REYNOLDS NUMBER"

Journal of Aircraft, Vol. 54, No. 3, May-June 2017, pp. 1025-1034.

This paper examines the application of formation flight to micro air vehicles regarding possible power savings. Results of an experimental investigation on echelon formations using low-aspect-ratio ($AR = 2$) flat plate rectangular wings at low Reynolds number ($Re = 35,000$) are presented. One, two, and three-wing configurations are tested in a low-speed wind tunnel. To quantify the power savings by lift enhancement and drag reduction, the aerodynamic loads acting on each wing are measured using specific balances while the trailing wings of the formation are being traversed laterally and vertically in fine steps. In addition, the flow fields of the wing wakes are measured using particle image

velocimetry. The force and flow field measurements show that the optimal positions for lift enhancement appear at slightly spanwise overlapping between the leading and trailing wings.

Korner, H.

"HERMANN SCHLICHTING'S WORK AND WAKE IN AIRPLANE-AERODYNAMICS"

Notes on Numerical Fluid Dynamics and Multidisciplinary Design, Vol. 102, 2009, pp. 18-38.

This paper gives a survey of the work of Hermann Schlichting in the field of airplane-aerodynamics. It includes his scientific work as well as his commitment in building up test facilities. It furthermore describes his role in the reconstruction of aerodynamics research after the war, when he became one of the key persons. Under his leadership the reconstruction of wind tunnels and the establishment of new priority fields in research took place. Subsequently, he introduced this new orientation of German aerodynamics research to the international community.

Korner, S. and Holzaepfel, F.

"MULTI-MODEL ENSEMBLE WAKE VORTEX PREDICTION"

Aircraft Engineering and Aerospace Technology, Vol. 88, Issue 2, 2016, pp. 331-340

Purpose Wake vortices that are generated by an aircraft due to lift constitute a potential danger to the following aircraft. To predict and avoid dangerous situations, wake vortex transport and decay models have been developed. Being based on different model physics, they can complement each other with their individual strengths. This paper investigates the skill of a Multi-Model Ensemble (MME) approach to improve prediction performance. Therefore, this paper aims to use wake vortex models developed by NASA (APA3.2, APA3.4, TDP2.1) and by DLR (P2P). Furthermore, this paper analyzes the possibility to use the ensemble spread to compute uncertainty envelopes.

Korner, S. and Holzaepfel, F.

"MULTI-MODEL ENSEMBLE WAKE VORTEX PREDICTION -- FURTHER DEVELOPMENT AND PROBABILISTIC ASSESSMENT"

AIAA Paper 2016-3438, June 2016, Washington, DC.

This paper investigates the capability of the Multi-Model Ensemble approach to improve both the deterministic and probabilistic forecast of wake vortex behavior. Therefore, the models D2P, APA 3.2, APA 3.4 and TDP 2.1 were provided within the framework of a NASA-DLR cooperation. In a previous study the Bayesian Model Averaging (BMA) approach, that computes the ensemble forecast as a weighted sum of PDDs, turned out to be promising. For this reason, the focus of this paper lies on the further development and assessment of this method. While the previously presented approaches did not consider that the error increases temporally, the new approach considers the growing

uncertainties. For training and evaluation wake vortex campaigns accomplished by NASA (DFW97, MEM95) and DLR (WakeMUC, WakeFRA, WakeOP) are employed.

Korner, S., Ahmad, N. N., Holzaepfel, F. and VanValkenburg, R. L.

"MULTI-MODEL ENSEMBLE WAKE VORTEX PREDICTION"

AIAA Paper 2015-3173, June 2015, Dallas, TX.

Several multi-model ensemble methods are investigated for predicting wake vortex transport and decay. This study is a joint effort between National Aeronautics and Space Administration and Deutsches Zentrum für Luft- und Raumfahrt to develop a multi-model ensemble capability using their wake models. An overview of different multi-model ensemble methods and their feasibility for wake applications is presented. The methods include Reliability Ensemble Averaging, Bayesian Model Averaging, and Monte Carlo Simulations. The methodologies are evaluated using data from wake vortex field experiments.

Korner, S., Ahmad, N. N., Holzaepfel, F. and VanValkenburg, R. L.

"MULTIMODAL ENSEMBLE METHODS FOR PREDICTION OF WAKE-VORTEX TRANSPORT AND DECAY"

Journal of Aircraft, Vol. 54, No. 5, September-October 2017, pp. 1849-1859.

Several multi-model ensemble methods are selected and further developed to improve the deterministic and probabilistic skills of individual wake-vortex transport and decay models. The different multi-model ensemble methods are introduced, and their suitability for wake applications is demonstrated. The selected methods include direct ensemble averaging, Bayesian model averaging, and Monte Carlo simulation. The different methodologies are evaluated employing data from wake-vortex field measurement campaigns conducted in the United States and Germany.

Korner, S., Solch, I., Holzaepfel, F., Abdelmoula, F. and Vechtel, D.

"PERFORMANCE OF ONBOARD WAKE-VORTEX PREDICTION SYSTEMS EMPLOYING VARIOUS METEOROLOGICAL DATA SOURCES"

WMO Aeronautical Meteorological Scientific Conference 2017, November 2017, Toulouse, France.

Wake vortices, generated by aircraft enroute, naturally descend towards lower flight levels. Due to the minimum vertical spacing the possibility for an aircraft at lower flight level to encounter wake turbulence seems small at first glance. However, 73 wake-turbulence incidents have been reported at upper flight levels between 2009 and 2012. Furthermore, in January a Challenger business jet experienced a severe wake encounter with several passengers injured and the aircraft being forced to perform an emergency landing. To reduce the risk of wake vortex encounters in-flight onboard wake

vortex forecasts can predict the position and strength of vortices generated by nearby aircraft. In this work the accuracy of wake-vortex predictions of DLR's wake encounter avoidance and advisory system (WEAA) is analyzed by means of data gathered from a flight test campaign in April 2014. The system is based on airborne data exchange between aircraft and allows pilots to avoid potentially dangerous wake-vortex encounters. As the vortex evolution is strongly controlled by atmospheric parameters, the acquisition of meteorological data is crucial for WEAA. The accuracy of the wake-vortex predictions is investigated, employing first the current automatic dependent surveillance (ADS-B) standard, which is then extended by additional meteorological data transmitted via telemetry, or data from numerical weather predictions (NWP).

Kornev, N. and Abbas, N.

"NUMERICAL SIMULATION OF THE TIP VORTEX BEHIND A WING OSCILLATED WITH A SMALL AMPLITUDE"

Journal of Aircraft, Vol. 54, No. 2, March-April 2017, pp. 828-835.

The aim of the present study is the validation of unsteady wing-wake simulations using different CFD models. Numerical URANS simulations reproduce increase of the maximum tangential velocities, streamwise vorticity, and vortex strength during pitch-down, compared with these during pitch-up. The level of difference between pitch-down and pitch-up values increases slightly with the frequency and angle of attack. Because the relaminarization is not modeled and the separations are not observed at small AOA, the reason for this difference is due to common delay effects, which are well known in aerodynamics and caused by formation of unsteady vortices. Overall, the agreement between URANS and measurements can be considered as satisfactory. The discrepancy between numerical results and measurements is due to four reasons: insufficient resolution of the vortex core, application of imperfect turbulence models, small number of simulated oscillation cycles, and measurement uncertainty. A strong discrepancy is observed in the range of small AOA in the pitch-up phase. It can be explained by the relaminarization leading to a significant change of the flow, which cannot be captured by turbulence models used in this note. This effect requires additional investigation in the future.

Kornev, N. V. and Basin, M. A.

"A WAY TO SPLIT THE NAVIER-STOKES EQUATIONS IN THE CONTEXT OF THE VORTEX METHOD"

Communications in Numerical Methods in Engineering, Vol. 14, Issue 4, April 1998, pp. 313-319

A numerical scheme has been obtained rigorously from the initial-boundary value problem for the Navier-Stokes (NS) equations in the context of the vortex method. The technique is based on a transformation of the NS equation into a parabolic equation which has an exact solution. The numerical scheme is derived by expanding the exact solution in Taylor series in powers of a small time-interval. Numerical implementation is developed with use of vortex particles to represent the vortex flow domain. The method is used to solve practical engineering problems. The technique can also incorporate turbulence modelling.

Kornev, N. V. and Reichert, G.

"THREE-DIMENSIONAL INSTABILITY OF A PAIR OF TRAILING VORTICES NEAR THE GROUND"

AIAA Journal, Vol. 35, No. 10, October 1997, pp. 1667-1669

A linear analysis of inviscid fluid is presented, indicating that trailing vortices undergo a growing sinusoidal instability in close vicinity to the ground and encounter it. However, in reality, the approaching vortices generate the boundary layer along the ground that separates and causes the primary vortices to follow a complicated trajectory.

Kornev, N., Treshkov, V. and Reichert, G.

"DYNAMICS OF THE TRAILING VORTICES NEAR THE GROUND"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany, pp. 425-434.

The first part of the paper is devoted to the trailing vortices dynamics in the near vortex wake of a lifting surface near the ground. The problem has been extensively investigated because of its historical importance in the ekranoplan application. In this paper we describe some specific features of the trailing vortices behavior near the ground. The second part of the paper focuses on the trailing vortices behavior in the far vortex wake. An important aspect of the present paper is the theoretical study of the three-dimensional Crow instability near the ground. Both the cases of inviscid and viscous flow have been considered. The developed analytical model in inviscid flow predicts three types of the vortex instability near the ground, depending on the dimensionless height of flight. The possible scenario of the vortex trailing instability and decay in ground effect has been proposed as a result of the theoretical analysis.

Kos, J., Blom, H. A. P., Speijker, L. J. P., Klompstra, M. B. and Bakker, G. J.

"PROBABILISTIC WAKE VORTEX INDUCED ACCIDENT RISK ASSESSMENT"

Third USA/Europe Air Traffic Management R&D Seminar, June 2000, Naples, Italy

New Air Traffic Management (ATM) concepts for departure and landing on busy airports might have a major impact on capacity if the wake vortex induced risks are better understood. The present wake vortex separation standards for the use of a single runway are often limiting capacity too much. To give ATM concept developers feedback with respect to the safety of new ATM concepts, a novel probabilistic methodology is under development for the assessment of wake vortex induced accident risks. The results of the safety assessment give insight in critical ATM design issues and thereby well-founded advice can be given on improvement of the design of the ATM concept. The probabilistic wake vortex induced accident risk assessment is based on recent progress in wake vortex research. Commonly accepted models for wake vortex evolution and wake encounter have been adapted and

integrated in the stochastic modelling and analysis setting of the TOPAZ (Traffic Organization and Perturbation AnalyZer) methodology. This paper outlines this probabilistic wake vortex induced accident risk assessment methodology and illustrates its initial application to the case of multiple aircraft landing on a single runway.

Kotsur, O. S. and Shcheglov, G. A.

"VISCOUS FLUID SIMULATION WITH THE VORTEX ELEMENT METHOD"

31st Congress of the International Council of the Aeronautical Sciences (ICAS 2018), September 2018, Belo Horizonte, Brazil.

Vortex methods have shown their effectiveness for several kinds of incompressible fluid dynamics problems, where the viscosity effects can be neglected. However, simulation of viscous flows via vortex methods meets difficulties because of the viscosity term in the vorticity evolution equation that needs to be resolved. In this paper we give a general overview of several viscosity models that we apply to the Vortex Element Method based on fragmentations. We consider three different approaches: Particle Strength Exchange, Diffusion-Velocity Method, and a hybrid scheme to approximate the viscosity term. Finally, we show two simple simulation examples of the diffusion of rectilinear vortex and vortex ring in viscous fluid.

Koumoutsakos, P.

"INVISCID AXISYMMETRIZATION OF AN ELLIPTICAL VORTEX"

Journal of Computational Physics, Vol. 138, 1997, pp. 821-857

The inviscid evolution of elliptical, nonuniform vorticity distributions is studied computationally using a high resolution Lagrangian (vortex) method with minimal numerical dissipation. The simulations reveal that the vortices evolve, through a process of filamentation, to a configuration consisting of a vortex surrounded by weak filamentary structures. The shape of the final configuration depends on the profile of the initial vorticity distribution. For the same ellipticity, relatively smooth profiles evolve to axisymmetric vortical structures, whereas sharper initial vorticity distributions result in robust non-axisymmetric configurations. A systematic convergence study is conducted to establish the accuracy of the method for long time inviscid simulations. To further assess the issue of axisymmetrization, we compare our results with related numerical and experimental studies.

Koumoutsakos, P., Leonard, A. and Pepin, F.

"BOUNDARY CONDITIONS FOR VISCOUS VORTEX METHODS"

Journal of Computational Physics, Vol. 113, 1994, pp. 52-61

This paper presents a Neumann-type vorticity boundary condition for the vorticity formulation of the Navier-Stokes equations. The vorticity creation process at the boundary, due to the no-slip condition, is

expressed in terms of a vorticity flux. The scheme is incorporated then into a Lagrangian vortex blob method that uses a particle strength exchange algorithm for viscous diffusion. The no-slip condition is not enforced by the generation of new vortices at the boundary but instead by modifying the strength of the vortices in the vicinity of the boundary.

Koziol, Jr., J. S.

"AN ASSESSMENT OF CURRENT METEOROLOGICAL DATA SYSTEMS AT LARGE AIRPORTS FOR WAKE VORTEX AVOIDANCE SYSTEMS"

PM-P-8, September 1974, DOT Transportation System Center, Cambridge, MA

The objective of this assessment was to determine to what extent current airport meteorological data systems can provide a basis for the formulation and implementation of a wake vortex prediction model. This involved an investigation of meteorological data systems at ten high-traffic density airports, weather forecasting services, and prediction model requirements.

Kozlov, V. E., Lebedev, A. B., Lyubimov, D. A. and Sekundov, A. N.

"DISTINCTIVE FEATURES OF THE TURBULENT FLOW IN A TRAILING VORTEX"

Fluid Dynamics, Vol. 39, No. 1, 2004, pp. 69-75

An analysis of the applicability of the well-known one-equation turbulence model of Spalart and Allmaras, which makes allowance for rotation and streamline curvature effects, to the description of the two-dimensional turbulent vortex flow downstream of the trailing edge of an aircraft wing and the three-dimensional interaction of the trailing vortex with the exhaust jets, is performed. A modification of the turbulence model is proposed and the results of numerical calculations are compared with the available experimental data.

Kraft, Jr., C. C.

"FLIGHT MEASUREMENTS OF THE TRAILING VORTICES OF AN AIRPLANE"

NACA TN-3377, March 1955, Langley Aeronautical Lab., Langley Field, VA

The disturbance created by the trailing vortices of an airplane can have a detrimental effect on the flight of another airplane passing through the wake. An attempt has been made to measure the velocity distribution and persistence of the trailing vortices of a propeller-driven fighter-type aircraft. This airplane was equipped with a smoke-generating device to mark the vortices. A jet airplane having a high-frequency angle-of-attack vane and a sensitive total-pressure instrument was used to fly through the vortices.

Kranepuhl, R., Shkarayev, S. and Planchenault, P.

"WINGTIP VORTEX MODIFICATIONS USING ALTERNATING JETS"

AIAA Paper 2016-3118, June 2016, Washington, DC.

The safe reduction of separation distance between airplanes can be achieved by modifying the wingtip vortices. Modifications in a near-field wake by using spanwise jets were studied on a NACA 0012 wing model. Experiments were conducted in the wind tunnel at 15 m/s and at an angle of attack of 7.5 degrees. Two chambers were integrated in the interior of the wing model with two angled jet slots in the wingtip. The jets pulsed at 10 Hz. The jet velocity distribution was quantified with the help of a hot-wire anemometry and PIV. To investigate the evolution of wingtip vortex, the phase-locked 2D PIV measurements were conducted at 5 streamwise stations. Studies include the baseline case, spanwise steady and pulsed jet blowing on the pressure and suction sides of the wing model, and alternating phase-shifted blowing of two jets. Steady jets displace wingtip vortices upward and outward from the wing tip. Under the pulsed blowing, the vortex center oscillates along the line inclined to the horizontal. When advecting downstream, the vortex is moving in a spiral trajectory rotating in the direction of the baseline vortex rotation. The maximum circulation for alternating blowing decreases downstream at a higher rate compared to other pulsed blowing. The size of the wingtip vortex core increases with distance from the wing.

Krasny, R.

"VORTEX SHEET COMPUTATIONS: ROLL-UP, WAKES, SEPARATION"

Lectures in Applied Mathematics, Vol. 28, 1991, pp. 385-402.

Chorin's vortex blob method has been proposed to extend vortex sheet motion past the singularity formation time, into the physically important roll-up regime. Basic questions are: (1) Does the vortex blob method converge to an infinite spiral as the smoothing parameter tends to zero? (2) Do vortex blob computations approximate the real fluid motion? This paper will present and discuss three computations which are relevant to these issues: a) periodic roll-up, b) wake patterns in a thin soap film, c) separation at a sharp edge.

Krasny, R.

"A VORTEX-DIPOLE SHEET MODEL FOR A WAKE"

Phys. Fluids A, Vol. 1, No. 2, February 1989, pp. 173-175.

A vortex model for a free shear layer with a wake component is proposed. The layer is represented by a curve which supports both a vortex sheet and a vortex-dipole sheet. The vortex sheet yields a monotonic velocity profile that connects the outer flows on either side of the shear layer. The vortex-dipole sheet captures the effect of oppositely signed vorticity that is present in the wake due to boundary layers upstream from the separation point. The equations governing a vortex-dipole sheet

are given and a temporal instability calculation for a free sinusoidal wake shows the development of a vortex sheet.

Krasny, R.

"COMPUTING VORTEX SHEET MOTION"

Proceedings of the International Congress of Mathematicians, 1990, Kyoto, Japan, pp. 1573-1583.

Coherent vortex structures occur in many types of fluid flow including mixing layers, jets and wakes. A vortex sheet is a mathematical model for such structures, in which the shear layer is approximated by a surface across which the tangential fluid velocity has a jump discontinuity. Vortex sheet motion belongs to the field of vortex dynamics, one of the main approaches to understanding fluid turbulence. Careful numerical experiments have helped advance the mathematical study of vortex sheets. Difficulties arise in computing vortex sheet motion due to short wavelength instability, singularity formation, and spiral roll-up. This paper reviews the problem of computing vortex sheet motion and presents several applications.

Krasny, R.

"COMPUTATION OF VORTEX SHEET ROLL-UP IN THE TREFFTZ PLANE"

J. Fluid Mech., Vol. 184, 1987, pp. 123-155

Two vortex-sheet evolution problems arising in aerodynamics are studied numerically. The approach is based on desingularizing the Cauchy principal value integral which defines the sheet's velocity. Numerical evidence is presented which indicates that the approach converges with respect to refinement in the mesh-size and the smoothing parameter. For elliptic loading, the computed roll-up is in good agreement with Kaden's asymptotic spiral at early times. Some aspects of the solution's instability to short-wavelength perturbations, for a small value of the smoothing parameter, are inferred by comparing calculations performed with different levels of computer round-off error. The tip vortices' deformation, due to their mutual interaction, is shown in a long-time calculation. Computations for a simulated fuselage-flap configuration show a complicated process of roll-up, deformation and interaction involving the tip vortex and the inboard neighboring vortices.

Krasny, R.

"VORTEX SHEET ROLL-UP DUE TO THE MOTION OF A FLAT PLATE"

International Symposium on Nonsteady Fluid Dynamics, Vol. 92, American Society of Mechanical Engineers, 1990, pp. 449-453.

The vortex-blob method is extended to compute vortex sheet separation at a sharp edge. A smoothing parameter controls the amount of detail occurring in the rolled-up spiral. Calculations are presented for the case of vortex sheet roll-up due to an impulsively started flat plate.

Krasny, R.

"NUMERICAL SIMULATION OF VORTEX SHEET EVOLUTION"

Fluid Dynamics Research, Vol. 3, 1988, pp. 93-97.

Recent research on the numerical simulation of vortex sheet evolution is discussed. Applications are presented to a periodic vortex sheet and to the vortex sheet shed behind a finite-span wing.

Krasny, R.

"COMPUTATION OF VORTEX SHEET ROLL-UP"

Proceedings of the UCLA Workshop on Vortex Methods, Lecture Notes in Mathematics, Vol. 1360, 1988, Springer, pp. 9-22.

In this article we shall review some recent developments for computing vortex sheet roll-up. First, results for the periodic vortex sheet will be reviewed. Then an application to some vortex sheet problems occurring in aerodynamics will be discussed in more detail. Finally, some open questions and directions for further research will be summarized.

Krause, E.

"BREAKDOWN OF SLENDER VORTICES: THE STATE OF THE ART"

In Vortex Dominated Flows, edited by D. Blackmore, E. Krause and C. Tung, 2005, World Scientific, New Jersey, Chapter 8, pp. 135-156.

The flow near the axis of slender vortices is investigated with particular emphasis on the deceleration of the axial flow, leading to a stagnation point and bursting or breakdown of the vortex. The Euler equations are reduced for steady, inviscid, incompressible, axially symmetric flow in a stream tube of small radius. The angular velocity is found to be directly proportional to the axial velocity component, implying that a deceleration of the axial flow can cause the angular velocity to vanish and breakdown to occur. The extension of the analysis to viscous incompressible flow identifies a thin viscous layer immediately upstream of the stagnation point, its thickness being inversely proportional to the Reynolds number. An approximate solution for the viscous flow shows that the angular velocity does not vanish at the stagnation point of the axial flow. The results are compared with experimental and numerical data of the recent literature.

Krause, E.

"ON VORTEX LOOPS AND FILAMENTS: THREE EXAMPLES OF NUMERICAL PREDICTIONS OF FLOWS CONTAINING VORTICES"

Vortex motion plays a dominant role in many flow problems. This article aims at demonstrating some of the characteristic features of vortices with the aid of numerical solutions of the governing equations of fluid mechanics, the Navier-Stokes equations. Their discretized forms will first be reviewed briefly. Thereafter three problems of fluid flow involving vortex loops and filaments are discussed. In the first, the time-dependent motion and the mutual interaction of two colliding vortex rings are discussed, predicted in good agreement with experimental observations. The second example shows how vortex rings are generated, move, and interact with each other during the suction stroke in the cylinder of an automotive engine. The numerical results, validated with experimental data, suggest that vortex rings can be used to influence the spreading of the fuel droplets prior to ignition and reduce the fuel consumption. In the third example, it is shown that vortices can also occur in aerodynamic flows over delta wings at angle of attack as well as pipe flows: of particular interest for technical applications of these flows is the situation in which the vortex cores are destroyed, usually referred to as vortex breakdown or bursting. Although reliable breakdown criteria could not be established as yet, the numerical predictions obtained so far are found to agree well with the few experimental data available in the recent literature.

Krause, E.

"A CONTRIBUTION TO THE PROBLEM OF VORTEX BREAKDOWN"

In Aerodynamic of Vortical Type Flows in Three Dimensions, AGARD-CP-342, July 1983, pp. 26-1 - 26-4.

Associated with the breakdown process is the formation of a stagnation point on the axis of the vortex. This requires the deceleration of the axial velocity component, which must be enforced by a positive axial pressure gradient. The analysis presented here shows, how the pressure gradient along the axis of the vortex is influenced by the radial and azimuthal velocity components. An explicit expression for $dp/dx(x,0)$ can be obtained by integration of the momentum equation for the radial velocity component with respect to the radial and subsequent differentiation of the integral with respect to the axial direction. In an order of magnitude analysis, it is then demonstrated that for large Reynolds numbers one component of the frictional force in the azimuthal direction cannot be neglected. In order to obtain an estimate for the pressure gradient rigid body rotation is assumed for the vortex core, and a distribution similar to that of a potential vortex $w = kr$ to the $-n$ power, for the outer portion. The estimate shows that a positive axial pressure gradient can exist only, if the radial velocity component is positive and if the exponent n is less than unity. It is also verified that a potential vortex cannot support an axial pressure gradient, that the pressure gradient in magnitude is directly proportional to the square of the maximum of the azimuthal velocity, referenced to the freestream velocity.

Krause, E.

"STAGNANT VORTEX FLOW"

Acta Mechanica, Vol. 209, 2010, pp. 345-351.

With the aid of the vorticity transport equation, it is shown that in inviscid, incompressible, axially symmetric vortex flow the axial vorticity component near the axis of the vortex approaches zero if the axial velocity component approaches a stagnation point, and vice versa, the axial vorticity component is increased, if the axial flow is accelerated. This result, obtained in earlier investigations by simplifying the momentum equations for the neighborhood of the axis of the vortex, is already contained in the vorticity transport equation as formulated by von Helmholtz in 1858. In laminar flow, with viscous forces acting near the stagnation point, the angular velocity does not necessarily vanish with the axial velocity component. These questions are discussed in the following.

Krause, E.

"ON AN ANALOGY TO THE AREA-VELOCITY RELATION OF GASDYNAMICS IN SLENDER VORTICES"

Acta Mechanica, Vol. 201, 2008, pp. 23-30.

Inviscid compressible flow in a slender longitudinal vortex with the axis parallel to the main flow direction is discussed. The Euler equations for steady, axially symmetric flow are simplified for the neighborhood of the axis of the vortex. The resulting relations, expressing the angular velocity in terms of the axial mass flow, when recast and integrated, represent an analogy to the area-velocity and the area-Mach number relation of one-dimensional gas dynamics. By restricting the analysis to the flow in a Rankine vortex with constant stagnation enthalpy, the static pressure on the axis can be related to the free-stream pressure far away from the axis and the maximum value of the azimuthal velocity. The influence of a radial wake-like distribution of the axial velocity component on the axial pressure is discussed. Its dependence on variable external boundary conditions is given. A condition is formulated, which must be satisfied for the formation of a free stagnation point on the axis.

Krause, E.

"BREAKDOWN OF COMPRESSIBLE SLENDER VORTICES"

Computational Science and High Performance Computing II, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 91, 2006, pp. 1-12.

Slender vortices of compressible flow are studied; in particular, the deceleration of the axial flow to a free stagnation point on the axis, causing bursting or breakdown of the vortex. Steady, inviscid, compressible, axially symmetric flow conditions are assumed to enable a reduction of the Euler equations for a stream tube of small radius. The angular velocity near the axis is shown to be directly proportional to the axial mass flux, indicating that a decelerated axial flow can cause the angular velocity to vanish and breakdown to occur. This behavior is reversed in supersonic flow. A breakdown criterion is derived for a Rankine vortex with isentropic and normal-shock deceleration of the axial flow. The results are compared with available experimental data.

Krause, E.

"REVIEW OF SOME VORTEX RELATIONS"

ICASE Report No. 84-46, Hampton, VA, September 1984.

The evaluation of the circulation from numerical solutions of the momentum and energy equations is discussed for incompressible and compressible flows. It is shown how artificial damping directly influences the time rate of change of the circulation.

Krause, E.

"SHOCK INDUCED VORTEX BREAKDOWN"

International Conf. on the Methods of Aerophysical Research, July 2000, Novosibirsk, Russia, pp. 109-114.

Breakdown of longitudinal vortices occurs as well in supersonic external and internal flows as in incompressible flows. Although a large number of theoretical and experimental investigations was carried out on the latter in the past decade, a criterion according to which the various modes of breakdown can be predicted, could not be derived as yet. Nevertheless, the formation of a free stagnation point on the axis is confirmed as a necessary condition for breakdown to occur. In a recent investigation P. Huerre and his coworkers cast this condition into a simple form, which yields results that are in good agreement with experimental data. In the present paper considerations like those just mentioned will be extended to compressible flows. Stagnation point criteria will be derived for a Rankine vortex first for isentropically decelerated axial flow and then for the case of transition through a normal shock.

Krause, E., Schroder, W., Klass, M. and Thomer, O.

"INTERSECTION OF SLENDER LONGITUDINAL VORTICES BY SHOCK WAVES"

ICCES, Vol. 5, No. 1, 2008, pp. 41-46.

In supersonic flow the leading-edge vortex of delta wings can encounter intersection by an oblique or a normal shock. The resulting interaction between the two influences the aerodynamic forces; in particular the lift, especially if vortex breakdown occurs. This problem was studied in an idealized form by assuming an isolated slender vortex being intersected by an oblique and a normal shock, respectively. The investigation was carried out in two coordinated companion studies, one using numerical solutions of the Euler and Navier-Stokes equations, and the other experimental techniques, i.e. flow visualization methods, and Laser-Doppler and particle-image velocimetry. The measurements yielded profiles of the axial velocity component, visualizations of the shock deformation, and the deflection of the vortex core for the case of the oblique-shock-vortex interaction. The numerical solutions yielded detailed profiles of all flow quantities including those of vortex breakdown.

Krause, M. C., Eberle, W. R., Miller, G. M. and Gorzynski, E. J.

"INVESTIGATION OF WIND CONDITIONS DURING EARLY MORNING HOURS AT LOS ANGELES INTERNATIONAL AIRPORT"

FAA-RD-77-116, October 1977, Lockheed Missiles & Space Co., Huntsville, AL

Los Angeles International Airport (LAX) uses a unique runway utilization pattern to minimize noise pollution between midnight and 0600. During these hours, all approaches are conducted to the east, and all takeoffs are conducted to the west. The low-altitude portions of all takeoff and landing operations are thereby conducted over the Pacific Ocean. During these operations, pilots have occasionally reported encountering unusual wind conditions. It is the objective of this study to use the Lockheed-Huntsville mobile laser Doppler unit velocimeter unit to monitor winds and wake vortices in the approach zone of runway 6R to identify the sources of the wind anomalies reported by the pilots. No incidents of pilot-reported wind anomalies occurred during the five-week data collection period.

Krause, M. C., Morrison, L. K., Craven, C. E., Logan, N. A. and Lawrence, T. R.

"DEVELOPMENT OF THEORY AND EXPERIMENTS TO IMPROVE UNDERSTANDING OF LASER DOPPLER SYSTEMS"

LMSC-HREC TR D306632, June 1973, Lockheed Missiles & Space Company, Huntsville, Alabama.

This final report documents work conducted during the period January 1971 through June 1973. It encompasses theoretical, analytical, and experimental studies, the object of which was to improve understanding of laser Doppler system operation for remote measurement of wind motion. An evaluation of the feasibility of three velocity component measurements was also conducted, and further optimization and design of new systems were accomplished.

Krause, M. C., Wilson, D. J., Howle, R. E., Edwards, B. B. and Craven, C. E.

"REMOTE MEASUREMENT UTILIZING NASA'S SCANNING LASER DOPPLER SYSTEM, VOLUME I: LASER DOPPLER WAKE VORTEX TRACKING AT KENNEDY AIRPORT"

LMSC-HREC-TR-D496633-V1, March 1976, Lockheed Missiles & Space Co., Huntsville, A.

Test operations of the Scanning Laser Doppler System (SLDS) at Kennedy International Airport (KIA) during August 1974 through June 1975 are reported. A total of 1619 data runs was recorded with a totally operational system during normal landing operations at KIA. In addition, 53 data runs were made during cooperative flybys with the CV-880 for a grand total of 1672 recorded vortex tracks. Test crews were at KIA for 31 weeks, of which 25 weeks were considered operational and the other six were packing, unpacking, setup and check out. Although average activity equates to 67 recorded landing operations per week, two periods of complete runway inactivity spanned 20 days and 13 days, respectively. The operation frequency therefore averaged about 88 operations per week.

Kriebel, A. R.

"PARTICLE TRAJECTORIES IN A GAS CENTRIFUGE"

Journal of Basic Engineering, September 1961, pp. 333-339.

The motion of spherical particles injected into a cylinder of gas which rotates as a solid body has been studied. The particle trajectory is expressed explicitly as a function of two dimensionless parameters: an injection-velocity parameter and an inertial parameter which is roughly the ratio of centrifugal force to drag force on the particle. The main results are the dependence on particle size of the time for particles to be centrifuged and of deposition angle. These results indicate performance limitations for an idealized cyclone separator and a centrifugal particle-size analyzer. Experimental data are presented for an air centrifuge which was designed to approximate the analytical flow model. Reasonably good agreement with theoretically predicted deposition angles was found for spherical glass beads and irregularly shaped chalk crystals, even for Reynolds numbers in excess of the Stokes flow regime for which the analysis applies. Particles as small as 2 microns may be classified with the present centrifuge configuration; however, by modification it might be used to classify particles in the submicron-size region.

Krishnamoorthy, S. and Marshall, J. S.

"THREE-DIMENSIONAL BLADE-VORTEX INTERACTION IN THE STRONG VORTEX REGIME"

Physics of Fluids, Vol. 10, No. 11, November 1998, pp. 2828-2845

A study of three-dimensional interaction between a blade and an initially columnar vortex was performed using flow visualization experiments and computer simulations for problems where the blade is translated normal to and impacts upon the vortex core. The reported research focuses on cases where the vortex is sufficiently strong that the blade boundary layer separates before the blade penetrates the vortex core. The study examines the topology and evolution of the separated secondary vorticity from the blade and its interaction with the primary vortex. In particular, it is observed that the separated vorticity from the blade has the form of a series of vortex loops that wrap around the outer surface of the primary vortex core and spread both upstream and downstream along the vortex axis. Both the initial formation of these vortex loops and their eventual interaction with the primary vortex are investigated. Computations based on a series of idealized models of the secondary vorticity are performed in order to examine the primary vortex response to wrapped vortex loops.

Krishnamoorthy, S., Gossler, A. A. and Marshall, J. S.

"NORMAL VORTEX INTERACTION WITH A CIRCULAR CYLINDER"

AIAA Journal, Vol. 37, No. 1, January 1999, pp. 50-57

Interaction of a columnar vortex with a long circular cylinder translated normal to the vortex axis is examined for the case where the cylinder diameter is much larger than the vortex core radius. The study focuses on understanding and quantifying the limitations of traditional vortex filament models

arising from vortex-induced separation of the cylinder boundary layer and vortex core shape deformation. These limitations are examined over a wide range of values of the impact parameter, defined as the ratio of the ambient normal velocity past the cylinder to the maximum vortex azimuthal velocity. Filament model predictions of vortex displacement are compared to experimental data both before and after vortex-induced boundary-layer separation. Experimental data are presented showing the importance of the ambient normal velocity to the cylinder in delaying vortex-induced boundary-layer separation, so that for cases with high impact parameter the flow is governed by inviscid effects even as the vortex moves quite close to the cylinder surface. The inviscid shape deformation of the vortex core is modest in the cases examined, even for close vortex-cylinder interaction, and is shown to have small effect on the surface pressure. The topology of secondary vorticity structures ejected from the cylinder boundary layer is examined using a two-color laser-induced fluorescence technique and is found to be qualitatively different for cases with high and low values of the impact parameter.

Krishnamurthy, R., Calhoun, R., Billings, B. and Doyle, J.

"WIND TURBULENCE ESTIMATES IN A VALLEY BY COHERENT DOPPLER LIDAR"

Meteorological Applications, Vol. 18, 2011, pp. 361-371.

In this paper, the effect of several turbulence parameters during various flow conditions in Owens Valley, deduced from coherent Doppler lidar data have been studied. Radial velocity structure functions are processed to estimate the turbulent kinetic energy (TKE) dissipation rate, integral length scale and velocity variance, assuming a theoretical model for isotropic wind fields. Corrections for turbulence measurements have been considered to address the complications due to inherent volumetric averaging of radial velocity over each range gate, noise of the lidar data, and the assumptions required to estimate effects of smaller scales of motion on turbulence quantities. Using data from the Terrain-induced Rotor Experiment (T-REX) in April-May 2006, vertical profiles of wind and turbulence parameters have been retrieved. During T-REX, unusual valley flows were detected by the lidar data, for example on 19 and 27 March 2006, daytime down-valley and night time up-valley flows, respectively, were observed. This paper focuses on understanding various turbulence parameters during these flow events. Turbulence estimates during daytime down-valley conditions were observed to be constant for most of the day, while for night time up-valley circumstances the turbulence increased steadily as the day progressed. Good comparison was observed between lidar and tower measurements, which validate the lidar turbulence retrieval assumptions. Comparison between TKE estimates from lidar and the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) model is also presented. This analysis will be helpful for improving the current turbulence parameterization schemes in COAMPS. Finally, differences and similarities in turbulence measurements between both the flow regimes are discussed.

Krishnamurthy, R., Choukulkar, A., Calhoun, R., Fine, J., Oliver, A. and Barr, K. S.

"COHERENT DOPPLER LIDAR FOR WIND FARM CHARACTERIZATION"

Wind Energy, Vol. 16, 2013, pp. 189-206.

Coherent Doppler lidar measurements are of increasing interest for the wind energy industry. Wind measurements are fundamental inputs for the evaluation of potential energy yield and performance of wind farms. Three-dimensional scanning Doppler lidar may provide a new basis for wind farm site selection, design, and optimization. In this paper, the authors discuss Doppler lidar measurements obtained for a wind energy development. The possibility of using lidar measurements to more fully characterize the wind field is discussed, specifically terrain effects, spatial variation of winds, power density and the effect of shear at different layers within the rotor swept area. Vector retrieval methods have been applied to the lidar data, and results are presented on an elevated terrain-following surface at hub height. The vector retrieval estimates are compared with tower measurements, after interpolation to the appropriate level. Doppler lidar data are used to estimate the spatial power density at hub height (for the period of the deployment). An example wind farm layout is presented for demonstration purposes based purely on lidar measurement, even though the lidar data acquisition period cannot be considered climatological. The strength of this approach is the ability to directly measure spatial variations of the wind field over the wind farm. Also, because Doppler lidar can measure winds at different vertical levels, an approach for estimating wind power density over the rotor swept area (rather than only the hub height) is explored. Finally, advanced vector retrieval algorithms have been applied to better characterize local wind variations and shear.

Krishnan, M.

"A MODEL FOR THE ONSET OF BREAKDOWN IN AN AXISYMMETRIC COMPRESSIBLE VORTEX"

Phys. Fluids, Vol. 8, No. 12, December 1996, pp. 3338-3345

A simple inviscid model to predict the onset of breakdown in an axisymmetric vortex is proposed. Three problems are considered: the shock-induced breakdown of a compressible vortex, the breakdown of a free compressible vortex, and the breakdown of a free incompressible vortex. The same physical reasoning is used in all three problems to predict the onset of breakdown. It is hypothesized that breakdown is the result of the competing effects of adverse pressure rise and streamwise momentum flux at the vortex centerline. Breakdown is assumed to occur if the pressure rise exceeds the axial momentum flux. A formula with no adjustable constants is derived for the critical swirl number in all three problems. The dependence of the critical swirl number on parameters such as upstream Mach number, excess/deficit in centerline axial velocity, and shock oblique angle is explored. The predictions for the onset of shock-induced breakdown and free incompressible breakdown are compared to experiment and computation, and good agreement is observed. Finally, a new breakdown map is proposed. It is suggested that the adverse pressure rise at the vortex axis be plotted against the axial momentum flux to determine the onset of breakdown. The proposed map allows the simultaneous comparison of data from flows ranging from incompressible breakdown to breakdown induced by a shock wave.

Kristensen, L.

"CUPS, PROPS AND VANES"

Riso-R-766(EN), August 1994, Riso National Laboratory, Roskilde, Denmark.

We discuss the dynamics of the cup anemometer, the propeller anemometer, and the wind vane. The phenomenological model by Kristensen (1993) is modified to describe the motion of the propeller anemometer. We use the well-known second-order differential equation describing the motion of the wind vane to study the properties of the vane itself and the vane in combination with a cup and a vane. It is argued that even the simplest question about how to record the signal from a cup anemometer has an ambiguous answer and can lead to a, not necessarily small, systematic error in the measured mean wind speed. We show how it is possible to measure the entire wind direction variance by utilizing the fact that an underdamped vane by 'overshooting' may compensate for the high-frequency variance loss if the damping coefficient is about 0.4. Finally, we discuss possible sources of bias on the measured mean-wind speed when using a propeller-vane anemometer. It turns out that this anemometer has the same type of biases from the lateral and vertical wind fluctuations as has the cup anemometer. In addition, there are bias contributions from misalignment between the mean wind and the propeller axis and from the translatory motion of the propeller itself with respect to the vertical wind-vane axis.

Kristensen, L.

"THE PERENNIAL CUP ANEMOMETER"

Wind Energy, Vol. 2, 1999, pp. 59-75.

A short version of the history of the cup anemometer precedes a more technical discussion of the special features of this instrument. These include its extremely linear calibration and the non-linearity of its response to wind speed changes. A simple conceptual model by Schrenk is used to demonstrate this and to explain why the cup anemometer can start from a zero rotation rate at zero wind to one corresponding to a sudden change in the ambient wind speed to a finite value. The same model is used to show that the cup anemometer should be characterized by a distance constant rather than by a time constant. The bias in the measured mean wind speed due to the random variations in the three velocity components is discussed in terms of standard, semi-quantitative turbulence models, and the main thesis is that this bias is overwhelmingly dominated by the fluctuations of the lateral wind velocity component, i.e. the wind component perpendicular to the mean wind direction, and not, as is often assumed, by the longitudinal wind velocity component. It is shown theoretically and tested experimentally that the bias due to lateral wind velocity fluctuations can be significantly reduced by means of a special data processing of the simultaneous signals from a cup anemometer and a wind vane. This means that, with care, the overall over-speeding can be reduced to less than 1 percent.

Kristensen, L. and Hansen, F.

"DISTANCE CONSTANT OF THE RISO CUP ANEMOMETER"

Riso-R-1320(EN), April 2002, Riso National Laboratory, Roskilde, Denmark.

The theory for cup-anemometer dynamics is presented in some detail, and two methods of obtaining the distance constant l are discussed. The first method is based on wind tunnel measurements: with a

constant wind speed the cup anemometer is released from a locked position of the rotor and the increasing rotation rate recorded. It is concluded that the rapid increase in rotation rate makes the method very inaccurate. The second method consists of an analysis of turbulent, atmospheric wind speed as measured by the cup anemometer and a fast-responding sonic anemometer with a spatial eddy resolution, which is significantly better than that which can be obtained by a cup anemometer. The ratio between the measured power spectra of the horizontal wind speed by the two instruments contains the necessary information for determining the response characteristics of the cup anemometer and thereby I . The conditions for this last method to be accurate are discussed. Field measurements are used to demonstrate how I is determined for the Riso cup anemometer, model P2546.

Kristensen, L., Hansen, O. F. and Hajstrup, J.

"SAMPLING BIAS ON CUP ANEMOMETER MEAN WINDS"

Wind Energy, Vol. 6, 2003, pp. 321-331.

The cup anemometer signal can be sampled in several ways to obtain the mean wind speed. Here we discuss the sampling of series of mean speeds from consecutive rotor rotations, followed by unweighted and weighted averaging. It is shown that the unweighted averaging creates a positive bias on the long-term mean wind speed, which is at least one order of magnitude larger than the positive bias from the weighted averaging, also known as the sample-and-hold method. For a homogeneous, neutrally stratified flow the first biases are 1-2 percent. For comparison the biases due to fluctuations of the three wind velocity components and due to calibration non-linearity are determined under the same conditions. The largest of these is the v -bias from direction fluctuations. The calculations pertain to the Riso P2546A model cup anemometer.

Kroo, I.

"DRAG DUE TO LIFT: CONCEPTS FOR PREDICTION AND REDUCTION"

Ann. Rev. Fluid Mechanics, Vol. 33, 2001, pp. 587-617

This article describes some of the fundamental ideas underlying methods for induced-drag prediction and reduction. A review of current analysis and design methods, including their development and common approximations, is followed by a survey of several approaches to lift-dependent drag reduction. Recent concepts for wing planform optimization, highly nonplanar surfaces, and various tip devices may lead to incremental but important gains in aircraft performance. Focusing on relatively high-aspect-ratio subsonic wings, the review suggests that opportunities for new concepts remain, but the greatest challenge lies in their integration with other aspects of the system.

Krothapalli, A., Buzyne, G. and Lourenco, L.

"STREAMWISE VORTICES IN AN UNDEREXPANDED AXISYMMETRIC JET"

Physics of Fluids, Vol. 3, Part A, No. 8, August 1991, pp. 1848-1851.

This Letter describes an experimental investigation demonstrating the existence of streamwise vortices in an under-expanded jet issuing from a convergent axisymmetric nozzle at a moderate pressure ratio of 5.1, and at a Reynolds number of 1,800,000. These vortices are quite strong and are in the supersonic region of the jet between the intercepting shock and the jet boundary. They seem to play a significant role by enhancing mixing between the ambient and jet fluids in the supersonic region of the jet. The scale of these vortices increases with downstream distance by a process of vortex merging.

Krothapalli, A., King, C. J. and Strykowski, P. J.

"THE ROLE OF STREAMWISE VORTICES ON THE SOUND GENERATION OF SUPERSONIC JETS"

AIAA Paper No. 1993-4320, Long Beach, CA, October 1993

Sound generation from supersonic axisymmetric jets in the presence of streamwise vortices was experimentally investigated. When streamwise structures are generated using small triangular tape elements placed in the laminar boundary layer upstream of the nozzle exit, they show insignificant effect on the far-field noise. Delta-tabs placed at the nozzle exit to generate streamwise vortices will reduce shock associated noise while increasing the turbulent mixing noise. Using a counterflowing nozzle, it is shown that increased mixing in supersonic jets may not result in noise suppression.

Krothapalli, K. R., Prasad, J. V. R. and Peters, D. A.

"STUDY OF A ROTOR FLAP-INFLOW MODEL INCLUDING WAKE DISTORTION TERMS"

RTO-MP-11, Proceedings RTO SCI Symposium on System Identification for Integrated Aircraft Development and Flight Testing, May 1998, Madrid, Spain, pp. 26-1 - 26-10.

For many years, analysts have been puzzled by the fact that the off-axis coupling of a helicopter exhibits the opposite sign in flight tests as compared to simulations. Recently, researchers have shown that the effect may be attributable to the bending of the wake during a pitching maneuver, which introduces a fore-to-aft gradient in induced flow that can reverse the predicted sign of the roll coupling. Other research has shown that this result can also be obtained with momentum and vortex theory. There are many issues still under debate regarding the magnitude of wake distortion and its effectiveness in predicting off-axis dynamics. In the present work, a generalized dynamic wake model is augmented to include wake distortion. This model is then coupled with a flap model for simulation in low-speed forward flight. Frequency responses from the simulation are collected with and without wake distortion, and these are compared with wind tunnel test data.

Krus, H. W., Haanstra, J. O., van der Ham, R. and Schreur, B. W.

"NUMERICAL SIMULATIONS OF WIND MEASUREMENTS AT AMSTERDAM AIRPORT SCHIPHOL"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 91, 2003, pp. 1215-1223

In this paper two typical results of numerical simulations of wind measurements at an airport are discussed. The first case deals with the long reach of some isolated individual 'roughness elements'. The positioning of the farms and haystacks result in a weak vortex which travels over a very long distance. The second case is about the influence of an industrial complex just outside the airport premises. In this case the actual wake behind the buildings is the dominant flow feature. The numerical simulations are able to explain the measured disturbances.

Kubberud, N., Oye, I. and Norstrud, H.

"ON THE INTERACTION BETWEEN TOPOGRAPHICAL WIND AND LANDING AIRCRAFT"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 24-1 to 24-12

The present paper gives a qualitative study of the flow interaction between a representative landing aircraft and the wind induced vortical flow. Separate numerical analysis for the wind flow over the given terrain and the flow structure around the lifting airplane is given. The interaction is performed by superposing the two solutions in various crossflow planes along the glide path direction of the aircraft. This leads to an estimate of the change of circulation for the lifting body and the associated need for corrective control forces.

Kucab, J. R.

"FREE WAKE ANALYSIS OF HELICOPTER ROTOR FLOW FIELDS USING A COUPLED VORTICITY EMBEDDING/FRACTIONAL STEP METHOD"

MS Thesis, August 2000, University of Tennessee, Knoxville, TN.

A hybrid CFD (Computational Fluid Dynamics) method combining a potential-based Vorticity Embedding method with an Euler solver is presented and validated for isolated rotor flows. First, a formulation of Vorticity Embedding is developed and validated for Cartesian grids. This formulation is utilized together with simple lifting lines to represent an isolated rotor in hover. The results for an isolated rotor are then compared with experiment. The method is then hybridized by coupling the Vorticity Embedding grid containing the rotor to a region containing a ground plane where a standard finite difference Euler solver is utilized. Initial results from this hybrid scheme are presented including a demonstration of the code's potential to calculate the ground vortex roll-up generated by a rotor in ground effect in the presence of a cross-wind.

Kucab, J. R. and Steinhoff, J.

"FREE WAKE ANALYSIS OF HELICOPTER ROTOR FLOW FIELDS USING A COUPLED VORTICITY EMBEDDING/FRACTIONAL STEP METHOD"

Report ARO 34260.3-EG-AAS, November 2000, University of Tennessee Space Institute, Tullahoma, TN.

A hybrid CFD (Computational Fluid Dynamics) method combining a potential-based Vorticity Embedding method with a Euler solver is presented and validated for isolated rotor flows. First, a formulation of Vorticity Embedding is developed and validated for Cartesian grids. This formulation is utilized together with simple lifting lines to represent an isolated rotor in hover. The results for an isolated rotor are then compared with experiment. The method is then hybridized by coupling the Vorticity Embedding grid containing the rotor to a region containing a ground plane where a standard finite difference Euler solver is utilized. Initial results from this hybrid scheme are presented including a demonstration of the code's potential to calculate the ground vortex roll-up generated by a rotor in ground effect in the presence of a cross-wind.

Kuchemann, D.

"TURBULENCE AND VORTEX MOTIONS"

Zeitschrift fur Flugwissenschaften, Vol 19, August-September 1971, pp. 305-308.

To find some concepts which might bring some order into what are usually described as turbulent motions, some thoughts are presented, which might lead to an interpretation of some of these motions in fluids of small viscosity in terms of inviscid flows involving vortex sheets and rolled-up vortex cores.

Kuchemann, D. and Weber, J.

"VORTEX MOTIONS"

Zeitschrift fur Angewandte Mathematik and Mechanik, Vol. 45, No. 7-8, December 1965, pp. 457-474

This work demonstrated that the key features of the vortex core flows are the same, whether the model used involves a vortex sheet in irrotational flow or a swirling flow with distributed vorticity. Some complete flows are described and the problems involved are briefly discussed, using the example of a lifting slender wing.

Kudela, H. and Kosior, A.

"PARALLEL COMPUTATIONS IN 3D VORTEX PARTICLE METHOD"

AIAA Paper No. 2011-3225, June 2011, Honolulu, Hawaii.

The paper presented an attempt to implement Vortex In Cell (VIC) method on Graphics Processing Units. The 3D VIC method was shortly described. To show correctness of the code the motion of a vortex ring was simulated. At first the numerical calculations were done on a single processor (x86) architecture. Disadvantage of the single processor computation is time consumption. To manage this problem, we switched to the parallel architecture. In our first approach to the multicore architecture, we tested algorithms for the solution of the algebraic system of equations that results from

discretization of the Poisson equation. For parallel computations CUDA architecture was used. We used the Multigrid and the Full Multigrid methods. It permitted us to speed up the solution of algebraic system using the Full Multigrid method 10 times. Finally, the whole VIC was implemented on the GPU. A 15-times speedup was obtained.

Kudela, H. and Regucki, P.

"VORTICITY PARTICLE METHOD FOR SIMULATION OF 3D FLOW"

Lecture Notes in Computer Science, Vol. 3037, 2004, pp. 356-363

The vortex-in-cell method for three-dimensional, viscous flow was presented. A viscous splitting algorithm was used. Initially the Euler inviscid equation was solved. Following that, the viscous effect was considered by the solution of the diffusion equation. The diffusion equation was then solved by the particle strength exchange (PSE) method. Validation of the method was tested by simulation of the leap-frogging phenomenon for two vortex rings moving along a common axis of symmetry and the reconnection phenomenon of two colliding vortex rings for viscous flow.

Kuethe, A. M.

"EFFECT OF STREAMWISE VORTICES ON WAKE PROPERTIES ASSOCIATED WITH SOUND GENERATION"

Journal of Aircraft, Vol. 9, No. 10, October 1972, pp. 715-720

Experiments in the turbulent-boundary-layer range of Reynolds numbers show that the Karman vortex street is suppressed and spanwise periodicity is induced in the wake behind an airfoil by the introduction of inclined surface waviness near the trailing edge. Both effects will reduce the intensity of sound sources in many applications.

Kuhn, G. D.

"LEAST-SQUARES ANALYSIS OF VELOCITY MEASUREMENTS IN THE WAKE OF AIRCRAFT WITH TAILORED SPAN LOADING"

NEAR TR-78, December 1974, Nielsen Engineering and Research Inc., Mountain View, CA

A method is presented for analyzing experimental velocity measurements behind aircraft with multiple wake vortices. The method assumes the vortices can be represented by inviscid vortices. The nonlinear mathematical expressions so produced are linearized around a 'first guess' of the positions and strengths of the vortices. The resulting expressions are solved for the unknown perturbations from linearity by the method of least squares. The 'first guess' is updated and the process repeated until the solution converges.

Kuhn, G. D. and Jacobsen, R. A.

"ANALYSIS OF WAKE VORTEX FLIGHT TEST DATA BEHIND A T-33 AIRCRAFT"

NASA CR-137669, April 1975, Nielsen Engineering & Research Inc., Mountain View, CA

Measurements of the vortex system behind a T-33 aircraft were obtained by a Learjet equipped with a boom carrying a three-wire, hot-wire anemometry probe and other instrumentation. Analysis of the measurements using a computerized geometric method indicated the vortices had a core radius of approximately 0.11 meter with a maximum velocity of 25 meters per second. No longitudinal instabilities, buoyant effects or vortex breakdowns were evident in the data which included vortex wake cross sections from 0.24 to 5.22 kilometers behind the T-33.

Kuhn, G. D. and Nielsen, J. N.

"ANALYTICAL STUDIES OF AIRCRAFT TRAILING VORTICES"

AIAA Paper No. 1972-0042, San Diego, CA, 1972.

The effects of turbulent mixing and buoyancy on the motion and persistency of a trailing vortex wake behind an aircraft are considered. A model for the characteristics of a turbulent vortex, based on an analogy to a turbulent boundary layer, is presented. A theory of trailing-vortex characteristics behind an aircraft is presented based on considerations of the angular and linear momentum of the vortex and the total pressure variation along the axis. Comparisons between the predictions of the theory and recent NASA wind tunnel data exhibit good agreement. The turbulent shear of the axial flow was shown to be the dominant mechanism for the growth of the core radius, the decay of the peak tangential velocity and the decay of the axial velocity defect.

Kuhn, R. E.

"AN INVESTIGATION TO DETERMINE CONDITIONS UNDER WHICH DOWNWASH FROM VTOL AIRCRAFT WILL START SURFACE EROSION FROM VARIOUS TYPES OF TERRAIN"

NASA TN D-56, February 1960, NASA Langley Research Center, Hampton, VA.

Results of an investigation with small-scale equipment of the conditions under which the downwash from a hovering vertical-take-off-and-landing (VTOL) aircraft will start surface erosion indicate that the onset of erosion depends only on the dynamic pressure of the outward flow of air near the surface. For a rotor or propeller at a height of about 1 slipstream diameter above the surface, this surface dynamic pressure was found to be equal to the disk loading. For the VTOL aircraft supported by a ducted fan, the surface dynamic pressure with the ducted fan exit at a height of about 1 slipstream diameter is equal to one-half the exit-area loading. The surface dynamic pressure decreases rapidly with increasing height of the VTOL device. Erosion of sand and loose dirt started at surface dynamic pressures of 1 to 3 lb/sq ft, which is in general agreement with helicopter experience. Thoroughly soaking the sand and loose-dirt surfaces increased the resistance to erosion to surface dynamic

pressures of 30 to 50 lb/sq ft. Spray from water started at surface dynamic pressures of 1.5 to 2.5 lb/sq ft. Sod withstood dynamic pressures up to about 1,000 lb/sq ft.

Kuibin, P. A. and Okulov, V. L.

"SELF-INDUCED MOTION OF HELICAL VORTICES"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany, pp. 53-62.

The self-induced velocity of helical vortices in an infinite space as well as in a cylindrical tube is studied. Investigation was based on an analysis of the formula for determination of the self-induced velocity of a helical vortex with a uniform vorticity distribution inside a core. A simple formula for the velocity, that permitted to fulfill its complete analysis, was derived for the first time with the help of an explicit separation of singularities in analytical solutions for velocity fields induced by an infinitely thin helical filament in an infinite space and in a cylindrical tube. As a result, the main factors are established that influence the velocity of vortices rotation and determine existence of immobile vortex structures as well as rotating in the opposite direction to the flow swirling.

Kuizhi, Y., Liangliang, C., Hu, L. and Yunliang, W.

"ANALYSIS OF JET BLAST IMPACT OF EMBARKED AIRCRAFT ON DECK TAKEOFF ZONE"

Aerospace Science and Technology, Vol. 45, 2015, pp. 60-66.

The jet blast impact of embarked aircraft on the takeoff zone is studied to support carrier-aircraft adaptation. The geometric model of carrier-aircraft system is built in CATIA Software and an unstructured mesh of the model is generated in Workbench Software. The jet blast impact of embarked aircraft on flight deck and jet blast deflector while taking off from takeoff zone is numerically simulated with standard k- ϵ and three-dimensional N-S equations based on CFD theory. Thermal coupling of wind over deck and jet blast is also taken into consideration. The distribution of temperature, pressure, velocity and streamline of the coupling flow is numerically simulated through Fluent Software and the temperature characteristics distribution on axes is also obtained. The results indicate: (1) the method presented in the paper can analyze fluid mechanics problems of complicated geometric models and obtain highly reliable simulation results; (2) the safe operation region for personnel, the suitable outfitting of jet blast deflector and proper layout of takeoff zone can be obtained.

Kulwatz, N.

"BEITRAGE ZUR BESTIMMUNG DER FLUGZEUGREAKTION BEIM EINFLOG IN WIRBELSCHLEPPEN SEHR GROSSER TRANSPORTFLUGZEUGE"

PhD Thesis, 2010, Technical University of Berlin, Berlin, Germany.

This thesis analyzes the influence of wake vortices resulting from very large transport aircraft, so-called 'mega-liners', on encountering aircraft. The analysis considers the vortex induced forces and moments acting on the encountering aircraft and the resulting dynamic behavior of manually controlled aircraft in real-time flight simulations. A flight mechanical model will be presented, which can describe the influence of small wind fields on the aircraft behavior within real-time flight simulation. Here the aerodynamic model takes a key role utilizing a lifting surface method. This lifting surface method is applied to the wing, the horizontal and the vertical tail plane and considers control surface deflections as well as flap positions. Furthermore, this aerodynamic model is suitable to calculate downwash distributions on the horizontal tail plane. Beyond that a vortex model is presented, which derives the wind velocities in wake vortices behind mega-liners. This model meets the high requirements of real-time flight simulations and describes the wake vortex as a pair of counter rotating vortices. The models are deployed initially to determine stationary forces and moments on two generic aircraft. In the analysis process variations of the encountering situation as well as variations of the wake vortex parameters are taking place. The focus of this thesis is directed on the analysis of the dynamic behavior of controlled aircraft during wake vortex approach. Therefore, measured data as well as pilot ratings are considered which are based on more than 700 simulated landing approaches. These landing approaches are conducted with several airline pilots on a state-of-the-art flight simulator with a visual and a motion system respectively. Recorded data is made accessible by statistic parameters of a descriptive analysis, to summarize the subjective ratings of several pilots during wake vortex encounter and to enable generic statements of the wake vortex hazard potential. Based on results from the flight simulations an equation is developed which describes the probability of a Go-Around maneuver. To determine the probability of a Go-Around maneuver both parameters of the wake vortex and parameters of the encountering aircraft are considered. The results of this investigation create a basis to determine a possible interference on aircraft which are following the mega-liners in approach and therefore to avoid unacceptable interferences by wake vortices during landing approach. [In German.]

Kumar, R. and Ghosh, A. K.

"PARAMETER ESTIMATION USING UNSTEADY DOWNWASH MODEL FROM REAL FLIGHT DATA OF HANSA-3 AIRCRAFT"

Aeronautical Journal, Vol. 115, No. 1170, September 2011, pp. 577-588.

The paper presents the estimation of longitudinal aerodynamic parameters from simulated as well as real flight data using an unsteady downwash model. The task of parameter estimation was accomplished using the Maximum Likelihood method in the frequency domain for the Hansa-3 aircraft. The presented work pertains to the aircraft having a semi-sweptback wing configuration, however, the work reported earlier considered a rectangular wing configuration. A simple vortex system was used to model downwash effects in the longitudinal equations of motion. First, it was established that the indicial lift function had a minor or negligible influence on aircraft motion and on the estimated aerodynamic parameters using simulated data for the configuration of Hansa-3 aircraft. Next, two parameter extraction algorithms were used for parameter estimation using simulated data (with unsteadiness only in downwash) and real flight data (Hansa-3 aircraft). The first algorithm included

unsteadiness only in downwash while the second neglected all the unsteady effects. It was observed from the results obtained that if unsteady effects were omitted from the parameter estimation algorithms, the extracted parameters included the effects of unsteady aerodynamics. Therefore, application of the extraction algorithm in the two modes provides a convenient means of separating steady-state and acceleration derivatives.

Kuntman, D., Brandao, R. C. P. and Bateman, C. D.

"SYSTEM AND METHOD FOR PREDICTING AND DISPLAYING WAKE VORTEX TURBULENCE"

US Patent 7,411,519 B1, August 2008.

A circuit and method for predicting an intersection of a host aircraft flight path with the wake vortex of another aircraft.

Kuntman, D., Brandao, R. CF. P. and Bateman, C. D.

"SYSTEM AND METHOD FOR PREDICTING AND DISPLAYING WAKE VORTEX TURBULENCE"

US Patent 6,703,945 B2, March 2004.

A circuit and method for predicting an intersection of a host aircraft flight path with the wake vortex of another aircraft.

Kupfer, M.

"SCHEDULING AIRCRAFT LANDINGS TO CLOSELY SPACED PARALLEL RUNWAYS"

ATM 2009, June-July 2009, Napa, CA.

An optimization model for a scheduling problem for closely spaced parallel approaches has been formulated. It takes temporal, pairing, sequencing, separation route and grouping constraints into account. Simulations investigated possible advantages of advanced scheduling methods over first-come-first-served scheduling. Also, this study evaluated the performance differences between the computation of optimal solutions using mixed integer linear programming and computing solutions using genetic algorithms. The influence of the scheduling method, as well as the influence of varying the sizes of the pairing and estimated arrival time windows, have been investigated. A set of 20 aircraft, distributed over 30 minutes, was used as traffic data. Inputs to the model were the earliest and latest estimated arrival times, aircraft wake category, aircraft pairing group and route information. A schedule at a specific coupling point where aircraft are coupled for parallel approach was then computed. It is generally expected that closely spaced parallel approaches greatly enhance arrival throughput. The results of this study underpin this assumption. Further findings were: (1) for a sufficiently varied traffic mix, advanced scheduling methods can improve arrival throughput by approximately one parallel approach pair per half an hour compared to first-come-first-serve scheduling in visual meteorological conditions. Average delay can be reduced over first-come-first-serve scheduling in visual meteorological

conditions by up to 36 percent. (2) schedules computed by an improved genetic algorithm are of similar quality as optimal solutions and can be made available after short computation times; (3) when minimizing make-span i.e., the arrival time of the last aircraft in a sequence, the size of the estimated arrival time window does not influence the characteristics of the computed schedules.

Kurgansky, M. V.

"A SIMPLE MODEL OF DRY CONVECTIVE HELICAL VORTICES (WITH APPLICATIONS TO THE ATMOSPHERIC DUST DEVIL)"

Dynamics of Atmospheres and Oceans, Vol. 40, Issue 3, December 2005, pp. 151-162

An asymptotic solution of inviscid Boussinesq equations for a 'dry convective Rankine vortex' with prescribed buoyant forcing is given. The obtained vortex solution demonstrates monotonic growth with height of the vortex core radius, which becomes infinite at a certain critical altitude, and the corresponding attenuation of the vertical vorticity. This idealized vortex is then embedded in a convectively unstable boundary layer; the resulting approximate vortex solution has been applied to determine the maximum rotational wind speed and diameter of dry convective dust-devil like vortices.

Kurkowski, R. L., Barber, M. R. and Garodz, L. J.

"CHARACTERISTICS OF WAKE VORTEX GENERATED BY A BOEING 727 JET TRANSPORT DURING TWO-SEGMENT AND NORMAL ILS APPROACH FLIGHT PATHS"

NASA TN D-8222, April 1976, NASA Ames Research Center, Moffett Field, CA

A series of flight tests was conducted to evaluate the vortex wake characteristics of a Boeing 727 (B727-200) aircraft during conventional and two-segment ILS approaches. Twelve flights of the B727, which was equipped with smoke generators for vortex marking, were flown and its vortex wake was intentionally encountered by a Lear Jet model 23 (LR-23) and a Piper Twin Comanche (PA-30). The tests showed that at a given separation distance there were no readily apparent differences in the upsets resulting from deliberate vortex encounters during the two types of approaches. Timed mappings of the position of the landing configuration vortices showed that they tended to descend approximately 91 m (300 ft) below the flight path of the B727. The flaps of the B727 have a dominant effect on the character of the trailed wake vortex. The clean wing produces a strong, concentrated vortex but as the flaps are lowered, the vortex system becomes more diffuse. Pilot opinion and roll acceleration data indicate that 4.5 n.mi. would be a minimum separation distance at which roll control of light aircraft (less than 5,670 kg (12,500 lb) could be maintained during parallel encounters of the B727's landing configuration wake.

Kurnosov, V. and Shkarayev, S.

"MODIFICATION OF VORTEX IDENTIFICATION METHOD BASED ON NORMALIZED ANGULAR MOMENTUM"

AIAA Paper 2017-3556, June 2017, Denver, CO.

The vortex identification method based on normalized angular momentum functions is revisited. In the original method, the scalar function used to locate the vortex center is not a Galilean invariant. In order to overcome this drawback, the function was modified by adding the convective velocity term defined as the average velocity over the vortex core. This method was then verified through numerical simulations of the Lamb-Oseen vortex in the freestream. Applications of this method to velocity fields obtained by Particle Image Velocimetry (PIV) through wind tunnel experiments on a wing and a propeller are discussed. This modified method with enhanced Galilean invariance showed an overall better accuracy and robustness of vortex detection.

Kurosaka, M., Cain, C. B., Srigrarom, S., Wimer, J. D., Dabiri, D., Johnson, III, W. F., Hatcher, J. C., Thompson, B. R., Kikuchi, M., Hirano, K., Yuge, T. and Honda, T.

"AZIMUTHAL VORTICITY GRADIENT IN THE FORMATIVE STAGES OF VORTEX BREAKDOWN"

J. Fluid Mech., Vol. 569, 2006, pp. 1-28.

This paper is motivated by an observation in the nascent state of vortex breakdown before it develops into a full-grown radial expansion, an initially straight vortex core first swells, and does so even in a straight pipe for no apparent reason. Although this initial swelling may be explained in many ways according to the perspectives chosen, we offer our own interpretation framed solely within vorticity dynamics: the radial swelling as well as the subsequent growth are induced by the azimuthal vorticity gradient decreasing downstream. The negative azimuthal vorticity gradient first appears at start-up and moves eventually into the region where the circulation reaches its steady-state value. The vorticity gradient can become negative without necessarily being accompanied by a sign-switch of the azimuthal vorticity itself. The key point - that the negative azimuthal vorticity gradient induces initial radial swelling and its growth - is demonstrated in two analyses. First, a kinematic analysis results in an equation for the radial velocity where the azimuthal vorticity gradient appears as a source term. Its solution shows, in general and explicitly, that the negative azimuthal vorticity gradient does induce radially outward velocity. Two heuristic examples serve to illustrate this point further. In the second analysis, using the equation of motion in the streamline coordinates, the negative azimuthal vorticity gradient is shown to diverge the meridional streamlines radially. A numerical simulation using a modified vortex filament method not only corroborates this role of the azimuthal vorticity gradient in initiating and promoting the radial expansion, but also adds details to track the formation process. Both analyses and simulation support our interpretation that the initial radial swelling and its subsequent growth are induced by the negative azimuthal vorticity gradient.

Kurosaka, M., Kikuchi, M., Hirano, K., Yuge, T. and Inoue, H.

"INTERCHANGEABILITY OF VORTEX-BREAKDOWN TYPES"

Experiments in Fluids, Vol. 34, 2003, pp. 77-86

To investigate the connection between the bubble and the spiral form of vortex breakdown, experiments were conducted: an external disturbance in the form of an azimuthally spinning waveform was imposed in a pipe. The azimuthal wave number was varied by adjusting the phase difference among four oscillating pistons mounted circumferentially on the pipe. By imposing a disturbance of zero azimuthal wave number, a spiral was transformed into a bubble, and this occurred only for selective piston frequencies; the vortex breakdown which altered from the spiral to the bubble moved upstream, where it remained as a bubble as long as the external disturbance remained. Once the disturbance was removed, the bubble returned to a spiral. By imposing a disturbance of azimuthal wave number $+1$ (the first circumferential mode rotating in the same direction as the mean swirl), a bubble was transformed into a spiral for selective piston frequencies, and the spiral moved downstream. These preferred frequencies were found to be the same as the unexcited frequencies observed in the spiral in its natural state. As long as the external disturbance was imposed, the breakdown altered from the bubble to the spiral remained as a spiral; once the disturbance was removed, the spiral reverted to a bubble. By imposing a disturbance with azimuthal wave number -1 (the first circumferential mode rotating in the opposite direction to the mean swirl), no change was detected in either bubble or a spiral. By imposing a disturbance with azimuthal wave number 2 (the second circumferential mode), for selective piston frequencies a bubble was transformed into what appears to be the so-called two-tailed type. Thus, it appears that hydrodynamic instability plays a role in interchanging vortex breakdown types, and a comparison with available stability theories is discussed.

Kurwatz, N.

"BEITRAGE ZUR BESTIMMUNG DER FLUGZEUGREAKTION BEIM EINFLUG IN WIRBELSCHLEPPEN SEHR GROSSER TRANSPORTFLUGZEUGE"

PhD Thesis, May 2010, University of Berlin, Berlin, Germany.

This thesis analyzes the influence of wake vortices resulting from very large transport aircraft, so-called 'mega-liners', on encountering aircraft. The analysis considers the vortex induced forces and moments acting on the encountering aircraft and the resulting dynamic behavior of manually controlled aircraft in real-time flight simulators. A flight mechanical model will be presented, which can describe the influence of small wind fields on the aircraft behavior within real-time flight simulation. Here the aerodynamic model takes a key role utilizing a lifting surface method. This lifting surface method is applied to the wing, the horizontal and the vertical tail plane and considers control surface deflections as well as flap positions. Furthermore, this aerodynamic model is suitable to calculate downwash distributions on the horizontal tail plane. Beyond that a vortex model is presented, which derives the wind velocities in wake vortices behind mega-liners. This model meets the high requirements of real-time flight simulations and describes the wake vortex as a pair of counter rotating vortices. The models are deployed initially to determine stationary forces and moments on two generic aircraft. In the analysis process variations of the encountering situation as well as variations of the wake vortex parameters are taking place. The focus of the thesis is directed on the analysis of the dynamic behavior of controlled aircraft during wake vortex approach. Therefore, measured data as well as pilot ratings are considered which are based on more than 700 simulated landing approaches. These landing

approaches are conducted with several airline pilots on a state-of-the-art flight simulator with a visual and a motion system respectively. Recorded data is made accessible by statistic parameters of a descriptive analysis, to summarize the subjective ratings of several pilots during wake vortex encounter and to enable generic statements of the wake vortex hazard potential. Based on results from the flight simulations an equation is developed which describes the probability of a Go-Around maneuver. To determine the probability of a Go-Around maneuver both parameters of the wake vortex and parameters of the encountering aircraft are considered. The results of this investigation create a basis to determine a possible interference on aircraft which are following the mega-liners in approach and therefore to avoid unacceptable interferences by wake vortices during landing approach.

Kurylowich, G.

"THE WAKE TURBULENCE RESEARCH PROGRAM AT AFFDL"

Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, Air Force Flight Dynamics Laboratory, AFFDL-TM-75-16-FGC, 1974, pp. 3-9

A review is given of the Flight Dynamics Laboratory wake turbulence program; the program was prompted by the evaluation of accidents and incidents within the Air Force. A large percentage of the vortex encounters occurred during military operations quite distinct from the usual civil related terminal operations (mid-air refueling, minimum interval takeoff, formation flight, and mixed mode operations with nearby helicopters). Future high-performance fighters will be more susceptible to vortex upsets because of their light weight and low moments of inertia. The primary concern of the Air Force is the near wake. The experimental and theoretical efforts on the near wake are reviewed as well as a vortex encounter simulation.

Kurylowich, G.

"A SIMPLIFIED VORTEX ENCOUNTER MODEL FOR SIMULATING WAKE TURBULENCE ON USAF TRAINERS AND SIMULATORS"

AFFDL-TM-75-91-FGC, June 1975, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, OH

A simplified model for the calculation of rolling moment on an aircraft encountering wake turbulence is presented. The model is implemented on appropriate trainers and simulators for the purpose of educating the pilots on the extent of a wake turbulence encounter as part of their training curriculum.

Kurylowich, G.

"A METHOD FOR ASSESSING THE IMPACT OF WAKE VORTICES OF USAF OPERATIONS"

AFFDL-TR-79-3060, July 1979, Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH

Experience as a consultant to the Safety Office at Norton AFB led to compiling the engineering tools presented so that this report can be used by engineering personnel to investigate future

incidents/accidents and existing USAF operations that are impacted by the vortical wake hazard. The approach presented is amenable to easy hand computations. Mixed airplane/helicopter operations can be assessed, since the engineering tools to determine the location and strength of the rotor downwash field behind a helicopter are presented. Finally, a simplified mathematical model is given to represent this hazard for use in USAF simulators, to make pilots aware of the problems associated with operating in wake-contaminated airspace.

Kurylowich, G.

"A STUDY OF AIR FORCE WAKE TURBULENCE ACCIDENTS"

AFFDL-TM-72-3-FGC, March 1972, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, OH.

USAF accident statistics have been analyzed for the 1965-1971 time-period. The number of accidents probably caused by wake encounters, as well as the percentage of total and terminal area losses they represent, are given. A short-term program for the study of wake turbulence as related to USAF operations is proposed.

Kurylowich, G.

"WAKE TURBULENCE ABATEMENT BY BLOWING AND OTHER MEANS"

Fluid Dynamics Panel, AGARD, 1973

The current state of knowledge concerning the turbulent breakup and bursting of aircraft trailing vortices is reviewed. Efforts towards the forcing of premature vortex breakup are placed in the context of an Air Force related wake turbulence program.

Kurylowich, G.

"ANALYSES RELATING TO AIRCRAFT VORTICAL WAKES"

AFFDL-TM-73-23-FGC, February 1973, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, OH

A comprehensive literature review of all analyses and experimental investigations related to vortical wake structure is presented. Various mathematical models for the flow field in the far wake are given and then compared to experiment. The possibility of causing premature vortex break-up by such means as wingtip spoilers and mass injection is also discussed.

Kurylowich, G. and Nelson, R. C.

"ANALYSIS OF A WAKE TURBULENCE HAZARD IN USAF OPERATIONS (T-38 ACCIDENTS)"

AFFDL-TM-74-132-FGC, June 1974, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, OH

Analyses related to the investigation of a T-38 accident which appeared to be caused by an encounter with the wake of an L-382 are presented. It is shown that the T-38 could have encountered wake turbulence through modelling the atmospheric propagation of the L-382 wake. The severity of the encounter is estimated through modelling of wake decay and the effects of dynamic encounters.

Kusmarwanto, I.

"GROUND EFFECT ON A ROTOR WAKE"

PhD Thesis, March 1985, Cranfield Institute of Technology, Cranfield, Bedford, UK.

The effect of the ground on a rotor wake in forward flight has been investigated experimentally in the working section of an 8ft x 4ft straight-through wind tunnel. A three bladed fully articulated rotor with a solidity ratio of 0.07 and diameter of 1.06m, powered by a hydraulic motor, has been tested at a height of 0.47 rotor diameter above a solid ground board which has an elliptical leading edge. Tests have been run at various low advance ratios (less than 0.1) with two collective pitch settings. A three-element hot wire anemometer probe has been used to measure the average value of the three components of velocity simultaneously in the forward half (advancing side) of the rotor wake and in the main stream surrounding it. The rotor wake and the ground vortices have been visualized by smoke. Surface flow patterns on the ground board have located the interaction region between the rotor wake and the oncoming flow on the ground board. Both experimental results and theoretical estimates show that the ground-induced interference is an upwash and a decrease in forward velocity. The upwash interference opposes the vertical flow through the rotor, and have large effects on the rotor performance in producing thrust. The streamwise interference decelerates the mainstream and becomes more noticeable as the wake boundary is approached.

Kusunose, K.

"DRAG PREDICTION BASED ON A WAKE-INTEGRAL METHOD"

AIAA Paper No. 1998-2723, June 1998, Albuquerque, NM.

This paper discusses the analytical aspects of the determination of drag acting on a model in a wind tunnel under subsonic or transonic flow conditions. The drag integral is derived from the integral form of the momentum equation to take the compressible flow effects into account. The drag integral can be broken down into profile drag (including wave drag) and induced drag. An analytical expression for induced drag has been developed to minimize the grid dependency problem, which is inherent in the numerical solution procedure. This analytical approach allows us to evaluate the effect of the wind tunnel walls on the drag. Predicted drag numbers from several different formulas are compared with experimental measurements.

Kusunose, K. and Crowder, J. P.

"EXTENSION OF WAKE SURVEY ANALYSIS METHOD TO COVER COMPRESSIBLE FLOWS"

Journal of Aircraft, Vol. 39, No. 6, November-December 2002, pp. 954-963

This paper summarizes the work accomplished over the last several years on wake-survey analysis method developments at Boeing. In this paper, Betz and Maskell's lift and drag equations are extended to cover compressible flows. The small perturbation method is employed to expand the general lift and drag equations in the momentum integral forms, assuming downstream states that differ only slightly from the state of approach. Introducing new, simpler, and cleaner expansion procedures, it is proven that both the lift and drag of an airplane model can be accurately predicted by simply measuring flow variables inside of the model wake region. This result enables the practical application of quantitative wake surveys for accurate lift and drag predictions of airplane models. To demonstrate the current lift and drag prediction capabilities, some wake survey analysis results from previously published data are re-calculated using newly developed lift and drag formulas. Since wake surveys are not needed outside of the model wake region, one complete wake survey analysis for a non-powered engine case, including data acquisitions and reductions, can now be finished in approximately 10-15 minutes. These wake survey analysis results demonstrate that both wake-integrated lift and drag typically agree with the internal strain-gauge balance to within a few percentage points.

Kusunose, K. and Odaka, Y.

"THE VELOCITY FIELD INDUCED BY A TRAILING VORTEX IN SUPERSONIC FLOW"

Japan Society of Aeronautical Space Sciences, Vol. 58, 2010, pp. 45-53.

To estimate the velocity field induced by a trailing vortex which is located along the free-stream direction in supersonic flow, we extend the Biot-Savart law, that is originally proven for subsonic flow, to supersonic flow. During the derivation we use the linearized perturbation potential equation that can be applied to both subsonic and supersonic (inviscid) flows. It is shown that our current formula reduces to the original Biot-Savart law when the flow speed reduces from supersonic to subsonic one. It is also shown in the appendix that the Kutta-Joukowski theorem is still applicable to supersonic flows within the supersonic thin-airfoil approximations.

Kusunose, K., and Crowder, J. P.

"EXTENSION OF WAKE-SURVEY ANALYSIS METHOD TO COVER COMPRESSIBLE FLOWS"

Journal of Aircraft, Vol. 39, No. 6, November-December 2002, pp. 954-963.

This paper summarizes the work accomplished over the last several years on wake-survey analysis method developments at Boeing. In this paper, Betz and Maskell's lift-and-drag equations are extended to cover compressible flows. The small perturbation method is employed to expand the general lift-and-drag equations in the momentum integral forms, assuming downstream states that differ only slightly from the state of approach. Introducing new, simpler, and cleaner expansion procedures, it is proven that both the lift and drag of an airplane model can be predicted accurately by simply

measuring flow variables inside of the model wake region. This result enables the practical application of quantitative wake surveys for accurate lift-and-drag predictions of airplane models. To demonstrate the current lift-and-drag prediction capabilities, some wake-survey analysis results from previously published data are recalculated. Because wake surveys are not needed outside of the model wake region, one complete wake survey analysis for a nonpowered engine case, including data acquisitions and reductions, can now be finished in approximately 10-15 min. These wake-survey analysis results demonstrate that both wake-integrated lift and drag typically agree with the internal strain-gauge balance to within a few percentage points..

Kusunose, K., and Crowder, J. P.

"EXTENSION OF WAKE SURVEY ANALYSIS METHOD TO COVER COMPRESSIBLE FLOWS"

AIAA Paper No. 2002-0829, January 2002, Reno, NV.

This paper summarizes the work accomplished over the last several years on wake-survey analysis method developments at Boeing. In this paper, Betz and Maskell's lift and drag equations are extended to cover compressible flows. The small perturbation method is employed to expand the general lift and drag equations in the momentum integral forms, assuming downstream states that differ only slightly from the state of approach. Introducing new, simpler, and cleaner expansion procedures, it is proven that both the lift and drag of an airplane model can be accurately predicted by simply measuring flow variables inside of the model wake region. This result enables the practical application of quantitative wake surveys for accurate lift and drag predictions of airplane models. To demonstrate the current lift and drag prediction capabilities, some wake survey analysis results from previously published data are re-calculated using newly developed lift and drag formulas. Since wake surveys are not needed outside of the model wake region, one complete wake survey analysis for a non-powered engine case, including data acquisitions and reductions, can now be finished in approximately 10-15 minutes. These wake survey analysis results demonstrate that both wake-integrated lift and drag typically agree with the internal strain-gauge balance to within a few percentage points.

Kusunose, K., and Crowder, J. P.

"EXTENSION OF WAKE SURVEY ANALYSIS METHOD TO COVER COMPRESSIBLE FLOWS"

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and drag prediction capabilities, some wake survey analysis results from previously published data are re-calculated using newly developed lift and drag formulas. Since wake surveys are not needed outside of the model wake region, one complete wake survey analysis for a non-powered engine case, including data acquisitions and reductions, can now be finished in approximately 10-15 minutes. These wake survey analysis results demonstrate that both wake-integrated lift and drag typically agree with the internal strain-gauge balance to within a few percentage points.

Kusunose, K., Crowder, J. P. and Miller, G. D.

"INSTALLED POWERED ENGINE EFFECTS ON DRAG USING A WAKE-INTEGRAL METHOD"

AIAA Paper No. 2000-2400, June 2000, Denver, CO.

This study focuses on the derivation of drag components of airplane models equipped with powered engines using the flow variables measured within the model wake region. To take the powered engine effects into account, the drag equation in the momentum integral form is modified by using the continuity and energy equations. Then, the drag equation is expanded into a perturbation form assuming downstream states that differ only slightly from the state of approach, to identify major individual drag components of an airplane model. Because of the work added by the powered engines, total temperature measurements (in addition to pressure measurements) are required at the wake survey station. However, it is shown for low-subsonic flows that the total temperature will not play a major role in the drag analysis. Because of the accelerated flows inside the jet plumes, higher order velocity terms in the drag equation are not necessarily small enough to be neglected inside the engine exhaust regions. Some of the preliminary wake survey analysis results of the High Wing Transport test (at the NASA Ames 12-Foot Pressure Wind Tunnel) are presented to demonstrate the powered engine capability in the drag analysis.

Kutz, B. M., Kessler, M. and Kramer, E.

"EXPERIMENTAL AND NUMERICAL EXAMINATION OF A HELICOPTER HOVERING IN GROUND EFFECT"

CEAS Aeronautical Journal, Vol. 4, Issue 4, December 2013, pp. 397-408.

This study collects experimental data of a helicopter hovering in ground effect and intends to prove the capability to compute the flow field around the measured helicopter rotor with the use of the flow solver FLOWer. Firstly, the wake trajectory of a Hughes 300C helicopter hovering in ground effect was obtained by introducing fog in the rotor disk, while visualizing the blade tip vortices with a laser light sheet and a high-speed camera. Secondly, the isolated rotor of the Hughes 300C was modeled numerically and computed with the block-structured second-order flow solver FLOWer from DLR, to provide a computational validation for full size rotors in ground effect hover. Blade dynamics were neglected and the rotor was trimmed to the experimental thrust. It was found that the flow solver can simulate the flow around a full-size helicopter rotor during hover in ground effect. The wake trajectories are convected downwards slightly faster than in the experiment. The radial wake path fits well with the experimental one until high wake ages, where the numerically as well as experimentally

reproduced trajectory becomes unstable. The development of the thrust value was analyzed with a Fourier transform. Disturbances due to the ground can be detected especially at higher harmonics of the blade passing frequency. For comparison, the rotor was also examined numerically out of ground effect. As expected, the oscillations are more periodic than close to the ground. An analysis of the performance data led to a benefit of 21 percent due to the ground effect.

Kuwahara, K.

"SIMULATION OF VORTEX-DOMINATED FLOW"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

Vortex structure behind a bluff body looks very complicated because of the separated vortices. Many experimental investigations have been done, but nobody yet can tell the dominant structure even for a simple sphere. On the other hand, in two dimensions, Karman vortex street is known to be most dominant. To find the essential three-dimensional structures, we computed these flows extensively and visualized them. From these computations, in this paper, we suggest the most important structure behind a bluff body is the U-shape vortex attached partially to the body and two tail flows down. Computation is now easier and more effective to see those phenomena than experiments.

Kuzmin, V. P.

"ANALYSIS OF THE VORTEX WAKE EFFECT ON AN AIRCRAFT IN LANDING APPROACH"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 227-238

The work outlines a method for calculating the parameters and shape of vortices in the atmospheric boundary layer and for calculating the spectral densities of unstable oscillations of four vortices (two actual and two imaginary), with atmospheric turbulence parameters and distances between the vortices being variable, the latter resulted from the interaction of the vortices with the ground surface. A technique is given for forming random realizations of the vortices to be used in statistical simulation of the following aircraft. A computer code created is intended for simulating random realizations of the vortex sheet and enables determining the location of vortex cores and cross-flow plane downwash angle distribution as a function of the range covered by the following aircraft. Included in the mathematical model as its constituents are the model of varying vortex core radius and circulation, model of the vortices transport in the ground proximity and the model of the random unstable oscillation of the vortices. The model presented is the modification of that described in (Kuzmin 1997). Numerical estimates are presented of the influence of various parameters of the wake mathematical model on the landing accuracy of the following aircraft.

Kuzmin, V. P.

"ESTIMATION OF WAKE-VORTEX SEPARATION DISTANCES FOR APPROACHING AIRCRAFT"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 209-224

This paper presents an approximate method of determining safe distances between aircraft of any leader-follower pair during approach operations. The need for maintaining certain distances between aircraft is associated with the possibility of the encountering of following aircraft with the vortex wake generated by a leading aircraft. Described in the paper are approximate mathematical models of the vortex wake and its effect on the following aircraft, which are needed to estimate safe distances. The mathematical model of the vortex wake considers the movement of vortices near the ground and the possibility of their decay due to effects of atmospheric turbulence. The degree of vortices hazard is determined by the rolling moment that they induce on the following aircraft. The wake-vortex separation distances are determined by a stochastic criterion.

Kuzmin, Y. V.

"THE NUMERICAL HISTORY OF AIRPLANE MANUFACTURING IN XX CENTURY"

31st Congress of the International Council of the Aeronautical Sciences (ICAS 2018), September 2018, Belo Horizonte, Brazil.

The database containing information about more than 18000 airplane models, created during XX century, their characteristics and production dates is prepared by author. Analysis of this database information gives answers on many questions about the aviation history. How many airplanes were built during XX century? How did it performances grow? What is common and different in the development of aviation industry of countries? When the rises and falls were happened, were their reasons local, national, or worldwide? Some answers are given in this report.

Kuznetsov, E. A. and Ruban, V. P.

"DYNAMICS OF VORTEX AND MAGNETIC LINES IN IDEAL HYDRODYNAMICS AND MHD"

Lecture Notes in Physics, Vol. 536, 1999, pp. 346-368

Vortex line and magnetic line representations are introduced for description of flows in ideal hydrodynamics and MHD, respectively. For incompressible fluids it is shown that the equations of motion for vorticity and magnetic field with the help of this transformation follow from the variational principle. By means of this representation it is possible to integrate the system of hydrodynamic type with the Hamiltonian. It is also demonstrated that these representations allow to remove from the noncanonical Poisson brackets, defined on the space of divergence-free vector fields, degeneracy connected with the vorticity frozenness for the Euler equation and with magnetic field frozenness for ideal MHD. For MHD a new Weber type transformation is found. It is shown how this transformation can be obtained from the two-fluid model when electrons and ions can be considered as two independent fluids. The Weber type transformation for ideal MHD gives the whole Lagrangian vector invariant. When this invariant is absent this transformation coincides with the Clebsch representation analog introduced in [1].

Kuznetsov, I. E. and Flaksman, I. S.

"APPROXIMATE CALCULATION OF THE VELOCITY FIELD AND THE MOTION OF VORTICES IN THE WAKE OF A LOW-FLYING BIPLANE"

Uchenye Zapiski, Vol. 8, No. 4, January 1977, pp. 92-96

The paper describes a method for calculating the velocity field some distance behind a low-flying biplane. The vortex wake is modeled as a system of four infinite free vortices, and the screening effect of the earth surface is considered by the introduction of four additional specularly reflected vortices. The motion of the vortices is studied as a function of flight altitude.

Kuznetsov, O. A. and Orlova, T. I.

"ON THE COMPUTATION OF DYNAMIC LOADING OF AN AIRCRAFT DUE TO A VORTEX WAKE"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 169-177

The problem of structural strength is one of the major problems in providing aircraft flight safety in the cases of encountering vortex wakes behind other aircraft. The method and computer codes were developed for calculating dynamic structural loading. The aircraft was considered to perform under vortex disturbances simultaneously both symmetric (pitching) and antisymmetric (lateral) motion with the excitation of corresponding modes of elastic structural oscillations. A series of parametric computations was performed for two airplanes with straight wings (weight 1300 and 22000 kg). The vortex wake was simulated with two vortex filaments with parameters variable in a wide range: the radius where the tangential velocity reaches its maximum, the distance between the vortices, the elevation of the encountering aircraft, its speed, the angle between the flight direction and the vortex axis. An analysis of transient processes has shown that the maximum load experienced by encountering aircraft is induced by the second vortex and the most dangerous from the standpoint of structural strength is the angle in the range of 90 ± 60 degrees. It was revealed that the maximum permissible vortex velocity for these two airplanes is of order 7-14 m/s. [In Russian.]

Kuznetsov, O. A. and Orlova, T. I.

"PREDICTION OF AIRCRAFT DISPLACEMENTS IN TURBULENT FLOW"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 265-273

Problem statement and a method for predicting vertical displacements of an aircraft immersed in a turbulent flow are outlined. Using the heavy IL-96 aircraft as an example, spectral characteristics of displacement of the aircraft center of gravity and wing tips were computed.

Kuznetsov, O. A. and Osminin, R. I.

"WIND-TUNNEL INVESTIGATION OF AN AIRCRAFT MODEL DYNAMIC LOADS DUE TO VORTEX GUSTS"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 157-168

This paper presents a description of a device in the form of a lattice of deflectable airfoils for generating vortex gusts. Examples of such gust flow fields are given for various laws of airfoils detection together with the characteristics of an aeroelastic aircraft model. The methodology and results of measurements of model dynamic response (wing bending moments) both in free flight and in the case of the fixed fuselage are described. An evaluation of experimental accuracy is presented.

Kuznetsov, O. A. and Vyshinsky, V. V.

"VORTEX-WAKE SAFETY: AIRCRAFT-STRENGTH ASPECTS OF THE PROBLEM"

AIAA Paper No. 1998-2523, Albuquerque, NM, June 1998

The whole safety problem of an aircraft penetrating a vortex wake is divided into three main parts: determination of the wake characteristics, calculation of a response to its action, and, finally, determination of safe distances, based on maximum permissible values of this response.

Kuznetsov, O. A., Orlova, T. I. and Chizhov, V. M.

"EVALUATION OF SAFE SEPARATION DISTANCES BETWEEN AIRCRAFT FROM THE STRENGTH STANDPOINT"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 138-147

This paper describes an approximate methodology developed for computing parameters of the vortex wake behind a wake generating aircraft (B-747) together with a method of determining dynamic loads due to the action of the wake on another aircraft. Results of computations are presented of distances (passage times) from a wake generating aircraft to a following aircraft at the instant of time when the latter experiences maximum allowable loads from the strength standpoint. Parametric investigations of effects of various factors are discussed, including wake characteristics, type of aircraft, flight speed and degree of atmospheric turbulence.

Kuznetsov, O. A., Orlova, T. I. and Osminin, R. I.

"DYNAMIC LOADING OF THE AIRCRAFT MODEL INDUCED BY VORTEX GUSTS: EXPERIMENTAL AND COMPUTATION"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 148-156

The paper presents computational and experimental methods used in investigation of dynamic loads on an aircraft model subject to vortex gusts generated in the wind-tunnel flow. Based on the comparison of computed results and experimental data, the applicability is assessed of the approach proposed to the determination of loads and separation distances between leading and following aircraft safe from the structural-strength standpoint and the conditions are found in which the strength issues for the second aircraft can affect the safe-separation distance.

La Roche, U. and La Roche, H. L.

"INDUCED DRAG REDUCTION USING MULTIPLE WINGLETS, LOOKING BEYOND THE PRANDTL-MUNK LINEAR MODEL"

AIAA Paper No. 2004-2120, Portland, Oregon, June 2004.

A redefinition of multiple winglet configurations is proposed in order to understand and facilitate exploiting the massive induced drag reductions of streamwise staggered multiple winglets, which, using the Prandtl-Munk vortex sheet model are not predicted. Multiple winglets are either staggered streamwise (feathered wingtips) or have no such stagger (Cone tip boxes, end-plates and other classic configurations). This contribution considers the fact, that we have on the one hand well understood and replicated winglet systems (no stagger) which are rendered with sufficient accuracy by the Prandtl-Munk model of a fixed vortex sheet in streamwise direction, free of drag, neglecting rolling up. On the other hand, selected cases new and old, such as the Spiroid, Split-Wing or the Winggrid are being reported which exhibit streamwise staggered winglets and where the experimental results point to much smaller induced drag than predicted with the Prandtl-Munk linear model. The paper shows, how including a grid effect of staggered multiple winglets on the deflected mass-flow of a wing system within linear models. The actual gap for conceptual understanding and calculating between experiment and prediction by linear models is bridged to a new perspective beyond the linear Prandtl-Munk model. Out of this new perspective follows a reassessment of selected multiple winglet configurations with superior performance potential.

La Roche, U. and Palffy, S.

"WING-GRID, A NOVEL DEVICE FOR REDUCTION OF INDUCED DRAG ON WINGS"

ICAS-1996, Sorrento, Italy, 1996.

A new wing-tip device for reduction of induced drag on wings is reported. Relative reductions of induced drag compared to elliptical planar wing up to 50% have been verified. The well-known equation of Spreiter and Sacks for rolled-up vortex geometry has two parameters, that define the relative induced drag of any wing and wingtip configuration: In the so-called Trefftz plane behind a wing the trailing vortices have spacing and vortex-core radius. The contribution of a wingtip to increase the vortex spacing and/or the vortex core radius for reduction of induced drag is used for the

classification of wingtips. Simultaneous exploitation of increasing vortex spacing and increasing vortex radius leads to configurations exceeding the potential of the known classic configurations by a wide margin. Known is the Spiroid by Dr. Louis Gratzer. Another is the WING-GRID treated in this paper. Both have been included in our wind tunnel verifications and are identified to belong to the same class. The paper reports the tests made and a preliminary description of the working principle of the wingtips belonging to this class as well as a description of the design information arrived at for the WING-GRID.

Labbe, O.

"LARGE-EDDY SIMULATION OF A TURBULENT JET AND WAKE VORTEX INTERACTION"

13th International Conference on Fluid Flow Technologies, September 6-9, 2006, Budapest, Hungary.

Temporal Large-Eddy Simulations of the interaction between a turbulent jet flow and a trailing vortex are described in this study. Three cases are analyzed: in the first one, the jet and the vortex axes are sufficiently well separated to not interact immediately, while in the second case the distance between the jet and the vortex is reduced to the half. In the last case the jet blows in the vortex core. In the two first cases, as the jet spreads, it is progressively deflected by the continuous input of crossflow momentum, so that it acquires azimuthal and radial component of velocity, causing the emergence of three-dimensional structures of azimuthal vorticity around it. When the jet and the vortex are superimposed, the turbulent kinetic energy does not increase, the vortex core is extremely buffeted. Results of the numerical simulation of the convection-diffusion of a passive scalar show that its distribution (initially in the jet) cannot penetrate inside the vortex core, due to its solid rotation, for the cases where the jet is initially outside the vortex and when it is injected in the vortex wake, its value remains very high and cannot get out of the vortex core.

Labbe, O. and Sagaut, P.

"RECONSTRUCTION OF INITIAL FIELD FROM EXPERIMENTAL DATA FOR NUMERICAL SIMULATIONS OF REALISTIC AIRCRAFT WAKES"

Progress in Computational Fluid Dynamics, Vol. 3, No. 1, 2003, pp. 1-12

The development of wake vortex behind an A300 Airbus model in high-lift configuration is computed by solving the unsteady Navier-Stokes equations for an incompressible fluid with a second order accurate scheme in time and space. Both two- and three-dimensional simulations are carried out, which allow us to compare the main vortex trajectory with data measured by three-component LDV system in the Onera facility. The study is focused on the way of initializing the computational entrance section based on the experimental data and the consequential effects of main vortex position up to nine wing spans downstream of the model. Several ways to reconstruct the initial velocity field for the simulations are investigated. The circulation distributions around the main vortex are compared and results obtained show that the circulation level is not a pertinent parameter to define a correct initialization. Numerical results show that a better agreement with experimental data is obtained when

a large domain is covered by experiments at the inlet section. A technique to reconstruct adequate initial data solving an inverse problem is also presented.

Labbe, O. and Sagaut, P.

"UNSTEADY WAKE VORTICES SIMULATION BEHIND A A300 MODEL"

AIAA Paper No. 2003-4022, Orlando, FL, June 2003

The development of wake vortex behind an A300 Airbus model in high-lift configuration is computed by solving the three-dimensional unsteady Navier-Stokes equations for an incompressible fluid with a second order accurate scheme in time and space. The vortices are liable to a global unsteadiness, in erratic displacement form around their mean position, called meandering. The aim of this study is to reproduce numerically the unsteady properties of the vortices and to compare the different frequencies with those measured experimentally and to analyze the squared coherence spectra to exhibit the combined movement of the main vortex.

labbe, O. and Sagaut, P.

"NUMERICAL SIMULATION BEHIND AN A300 AIRBUS MODEL"

ICMAR 2004, Novosibirsk, Russia, June 2004

The development of wake vortex behind an A300 Airbus model in high-lift configuration is computed by solving the three-dimensional unsteady Navier-Stokes equations for an incompressible fluid with a second order accurate scheme in time and space. The vortices are liable to a global unsteadiness, in erratic displacement form around their mean position, called meandering. The aim of this study is to reproduce numerically the unsteady properties of the vortices and to compare the different frequencies with those measured experimentally and to analyze the squared coherence spectra to exhibit the combined movement of the main vortex.

Labbe, O., Maglaras, E. and Garnier, F.

"LARGE-EDDY SIMULATION OF A TURBULENT JET AND WAKE VORTEX INTERACTION"

Computers and Fluids, Vol. 36, 2007, pp. 772-785

In this study, temporal large-eddy simulations of the interaction between a turbulent jet flow and a trailing vortex are described. Three cases are analyzed: in the first one, the jet and the vortex axes are sufficiently well separated to not interact immediately, while in the second case, the distance between the jet and the vortex is reduced by half. In the last case the jet blows in the vortex core. In the two first cases, as the jet spreads it is progressively deflected by the continuous input of crossflow momentum. Thus, it acquires azimuthal and radial components of velocity, causing the emergence of three-dimensional structures of azimuthal vorticity around it. When the jet and the vortex are superimposed, the turbulent kinetic energy does not increase, the vortex core is very buffeted.

Numerical simulation results of the convection-diffusion of a passive scalar show that its distribution (initially in the jet) cannot penetrate inside the vortex core due to its solid rotation. For the cases where the jet is initially outside the vortex and when it is injected in the vortex wake, its value remains very high and cannot get out of the vortex core. This phenomenon confirms the existence of a stabilizing 'dispersion buffer', adjacent to the core, which prevents amplification of the turbulence generated inside the core.

Labbe, O., Stumpf, E., Sagaut, P. and Rudnik, R.

"NEAR-TO MIDFIELD WAKE: NUMERICAL PREDICTION"

Proceedings 3rd ONERA-DLR Aerospace Symposium, Paris, France, June 2001, pp. S3-1/1-11

A chain of flow solvers for simulating the flow around an aircraft and the downstream evolution up to the midfield vortex wake is presented. In the first part the predictive capability of an Euler code using unstructured grids for the nearfield vortex wake calculation of the DLR-ALVAST model in landing configuration is demonstrated. The simulation quality of the vortex formation and spatial development is analyzed by comparison to experimental five-hole-probe and PIV data. In a second step, the development of the near- to midfield wake vortex behind a A300 Airbus model in high-lift configuration is computed with 2D Navier-Stokes calculations. A first validation is carried out with a comparison between the results of the near wake with those obtained in a wind tunnel. Furthermore, the calculated main vortex trajectory up to 80 spans is compared with data measured by laser tomography in the ONERA catapult facility.

Labbe, R. and Pinton, J.-F.

"PROPAGATION OF SOUND THROUGH A TURBULENT VORTEX"

Physical Review Letters, Vol. 81, No. 7, August 1998, pp. 1413-1416

We report an experimental study of sound propagation in the bulk of a homogeneous flow made of a single intense vortex in air. By using an adaptive-coherent average technique, the mean amplitude and phase of the distorted wave fronts are reconstructed. A large phase shift is observed on the wave fronts on either side of the 'shadow' region behind the vortex. The shape of the averaged amplitude, as a function of space coordinates, shows that caustics are also formed in the acoustic field. In a nonstationary flow, these effects make it possible to monitor the vortex strength and position.

Labrujere, T. E. and Devries, O.

"EVALUATION OF A POTENTIAL THEORETICAL MODEL OF THE WAKE BEHIND A WING VIA COMPARISON OF MEASUREMENTS AND CALCULATIONS"

NLR TR-74063-U, July 1974, National Aerospace Lab., Amsterdam, The Netherlands.

The validity of the representation of the wake by discrete trailing vortices as common practice in potential theoretical calculations is considered. Theoretical results, obtained with a method developed at NLR, are compared with experimental results obtained at NLB for a 30 deg sweptback wing. The shape of the vortex sheet as well as the velocity distribution downstream from the wing are predicted reasonably well; however, the wake model appears to be not completely satisfactory in the wing tip region. The numerical method requires improvement with respect to the description of the rolling up process of the vortex sheet.

Lacaze, L., Ryan, K. and Le Dizes, S.

"ELLIPTIC INSTABILITY IN A STRAINED BATCHELOR VORTEX"

J. Fluid Mech., Vol. 577, 2007, pp. 341-361.

The elliptic instability of a Batchelor vortex subject to a stationary strain field is considered by theoretical and numerical means in the regime of large Reynolds number and small axial flow. In the theory, the elliptic instability is described as a resonant coupling of two quasi-neutral normal modes (Kelvin modes) of the Batchelor vortex of azimuthal wavenumbers with the underlying strain field. The numerical study considers a system of two counter-rotating Batchelor vortices in which the strain field felt by each vortex is due to the other vortex. The characteristics of the most unstable linear modes developing on the frozen base flow are computed by direct numerical simulations for two axial flow parameters and compared to the theory. In both cases, a very good agreement is obtained for the most unstable modes. Less unstable modes are also identified in the numerics and shown to correspond to peculiar resonances involving Kelvin modes from branches of different labels.

Ladecky, S.

"IMPLEMENTATION OF AVOSS WAKE TURBULENCE MODEL INTO THE FAA'S AIRSPACE SIMULATION AND ANALYSIS FOR TERPS (ASAT) MONTE-CARLO SIMULATION SYSTEM"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

This presentation discusses three major points, namely: 1) The philosophy behind the development of the FAA's Airspace Simulation and Analysis for TERPS, also known as ASAT. 2) The Monte-Carlo style implementation of the wake turbulence model developed for AVOSS. 3) The manner the combined system has been utilized in a critical wake turbulence study regarding simultaneous parallel approaches to closely spaced parallel runways at San Francisco International Airport, California, USA.

Laforgia, A., Leoncini, X., Kuznetsov, L. and Zaslavsky, G. M.

"PASSIVE TRACER DYNAMICS IN 4 POINT-VORTEX FLOW"

Eur. Physics J. B, Vol. 20, 2001, pp. 427-440

The advection of passive tracers in a system of 4 identical point vortices is studied when the motion of the vortices is chaotic. The phenomenon of vortex-pairing has been observed and statistics of the pairing time is computed. The distribution exhibits a power-law tail with exponent about 3.6 implying finite average pairing time. This exponent agrees with its computed analytical estimate of 3.5. Tracer motion is studied for a chosen initial condition of the vortex system. Accessible phase space is investigated. The size of the cores around the vortices is well approximated by the minimum inter-vortex distance and stickiness to these cores is observed. We investigate the origin of stickiness which we link to the phenomenon of vortex pairing and jumps of tracers between cores. Motion within the core is considered and fluctuations are shown to scale with tracer-vortex distance r as r to the sixth power. No outward or inward diffusion of tracers are observed. This investigation allows the separation of the accessible phase space in four distinct regions, each with its own specific properties: the region within the cores, the reunion of the periphery of all cores, the region where vortex motion is restricted and finally the far-field region. We speculate that the stickiness to the cores induced by vortex-pairings influences the long-time behavior of tracers and their anomalous diffusion.

Lagerstrom, P. A. and Graham, M. E.

"METHODS FOR CALCULATING THE FLOW IN THE TREFFTZ-PLANE BEHIND SUPERSONIC WINGS"

Journal of the Aeronautical Sciences, March 1951, pp. 170-190.

By means of the linearized non-viscous theory, methods are developed, using the complex functions of conical flow, for finding downwash and sidewash in the Trefftz-Plane -- i.e., at an infinite distance downstream, behind a supersonic wing. Equations are derived which describe this flow field behind several types of 'flat plate' wings: the wide delta wing, the trapezoidal wing (wide delta wing with cutoff tips), and the delta control surfaces (a narrow delta wing, the two sides of which are deflected differentially). Graphs are included which show the results for these cases. As observed previously in connection with other cases, in the plane of the wing the flow field is characterized by infinite upwash straight behind the wing tips and, in the case of the delta wings and control surfaces, by a region of constant downwash behind the wing. These conditions are modified immediately upon moving above or below the plane of the wing. It is found that the flow field behind the delta control surfaces, the two sides deflected equal amounts in the opposite direction, does not vary with changes in Mach Number. In applying the results presented here, one must, of course, take into consideration corrections due to effects of fuselage interference, nonlinearity, viscosity, etc. These effects are not, however, the subject matter of this paper.

Lai, D. Y., Jacob, D., Lo, F. A. and Delisi, D. P.

"ASSESSMENT OF PULSED LIDAR MEASUREMENTS OF AIRCRAFT WAKES USING A LIDAR SIMULATOR: VORTEX POSITION ESTIMATES FOR IGE, LINKING, AND OBLIQUE VIEWING, AND DEPENDENCE OF VORTEX LIFETIME ON SNR"

AIAA Paper 2011-3197, June 2011, Honolulu, Hawaii.

A lidar simulator tool was developed to simulate realistic raw lidar signal data generated from a wake vortex velocity field as measured by the existing Lockheed Martin Coherent Technologies (LMCT) WindTracer pulsed lidar, currently used in the field to measure aircraft wake vortices. The raw lidar data is processed and the resulting product files are input into the existing LMCT Wake Vortex Processing Algorithm to estimate position and circulation strength versus wake age. The estimates from the Wake Vortex Processing Algorithm are then compared to truth data used to generate the raw lidar signal data. Accuracy of the Wake Vortex Processing Algorithm estimates of lateral and vertical position is evaluated by exercising the lidar simulator using input wake vortex fields based on analytical vortex models and 3-D Large Eddy Simulation computations for two aircraft types under IGE, OGE linking, and oblique viewing conditions. This study shows that the mean biases of the vortex position estimates for IGE and OGE linking vortices are small and similar to those for non-linking vortices in the OGE region reported in an earlier study. The use of the lidar at oblique angles relative to the trailing line vortices does not introduce significant differences in the position biases. An analysis of the vortex lifetime estimates with SNR variations suggests avoiding lidar measurements for SNRs below 0 dB.

Lai, D., Jacob, D. and Delisi, D. P.

"ASSESSMENT OF PULSED LIDAR MEASUREMENTS OF AIRCRAFT WAKE VORTEX POSITIONS USING A LIDAR SIMULATOR"

AIAA Paper No. 2010-7988, Toronto, Canada, August 2010.

A lidar simulator tool was developed to simulate realistic raw signal data generated from a wake vortex velocity field as measured by the existing Lockheed Martin Coherent Technologies (LMCT) pulsed lidar currently being used in field measurements of aircraft wake vortices. The raw lidar data is processed and the resulting product files are input into the existing LMCT's Wake Vortex Processing Algorithm for determining position and circulation strength versus wake age. Outputs from the Wake Vortex Processing Algorithm are then compared to the truth data used to generate the raw lidar signal data. Accuracy of the lidar measurements of lateral and vertical vortex positions is evaluated by exercising the lidar simulator, using input wake vortex fields based on analytical vortex models and 3-D Large Eddy Simulation numerical model outputs for different aircraft vortex, lidar and environment conditions. This study shows that the mean biases for the lidar measurements for vortex positions are small, about 4-7m for the lateral position and 1-3m for the vertical position.

Lai, J. Y.

"WAKE VORTEX VELOCITY TRACKING VIA KALMAN FILTERING"

Radar Systems Laboratory Electrical and Computer Engineering Technical Memorandum, May 1996, Clemson Univ., Clemson, SC

Current wake vortex detection methods basically involve the segmentation of the lidar return signal into partially overlapped data blocks and the wind speed estimation for individual data block using FFT or AR modeling. However, these methods can be very computationally involved, depending on the

dimension of the data vectors. The purpose of this memo is to introduce a computationally efficient way of tracking the line-of-sight velocity of a wake vortex pair. The idea is to model the pulsed lidar return signal from vortices as a dynamic (time-varying) second order AR process and to estimate the AR parameters via Kalman filtering. The data used in this memo are generated by RTI's simulation package which incorporates the AIAA standards model for vortex.

Laitone, E. V.

"LIFT-CURVE SLOPE FOR FINITE-ASPECT-RATIO WINGS"

Journal of Aircraft, Vol. 26, No. 8, August 1989, pp. 789-790.

Recently derived exact solutions for the lift produced by an elliptic planform flat plate in steady incompressible potential flow are applied to improve the commonly used approximations for the lift curve slope of finite aspect-ratio wings. An excellent approximation is derived for the initial lift-curve slope when the aspect ratio less than or equal to 2. For large aspect ratios, the lift-curve-slope equation is improved so that it can more accurately calculate the corresponding two-dimensional lift-curve slope from the wind tunnel test data of a finite-aspect-ratio wing.

Lake, H.

"AIRCRAFT WAKE VORTEX BEHAVIOR STUDY, METEOROLOGY AND AIRCRAFT VORTEX TRANSPORT AND DECAY"

ER-73-4299, July 1973, Raytheon Company, Sudbury, MA

This report identifies and defines the meteorological parameters that have been observed to affect the behavior of aircraft generated vortices. The most commonly observed effect (observed with smoke entrainment) was the drift of vortices with the mean wind. More recently other meteorological parameters have been identified as affecting the manner and rate at which vortices behave.

Lakshminarayan, V. K., Kalra, T. S. and Baeder, J. D.

"DETAILED COMPUTATIONAL INVESTIGATION OF A HOVERING MICROSCALE ROTOR IN GROUND EFFECT"

AIAA Journal, Vol. 51, No. 4, April 2013, pp. 893-909.

A compressible, structured, overset Reynolds-averaged Navier-Stokes-based solver is used to simulate a micro=hovering rotor in ground effect to demonstrate the capability of the code to provide accurate tip-vortex-flowfield predictions, and to provide a good understanding of the ground-wake interaction in conditions prevalent in helicopter brownout. The performance validation at different rotor heights above the ground shows good correlation with the experimental thrust and power measurements. A detailed comparison of the predicted tip-vortex flowfield shows good agreement with the vorticity contours and radial-velocity profiles obtained from the particle-image-velocimetry measurements

during experiments. The examination of the in-ground effect tip-vortex flowfield suggests high degree of instabilities close to the ground. The induced velocities arising from the proximity of the rotor tip vortices cause flow separation at the ground. An analysis of the eddy-viscosity contours near the ground indicates higher turbulence levels in the flowfield at smaller rotor heights above the ground. With a decreasing rotor height, the increased interactions between the tip vortices and the ground boundary layer result in the intermixing of eddy viscosity from the tip vortex to the ground boundary layer.

Lakshminarayan, V., Sitaraman, J. and Wissink, A.

"APPLICATION OF STRAND GRID FRAMEWORK TO COMPLEX ROTORCRAFT SIMULATIONS"

AIAA Paper 2016-3130, June 2016, Washington, DC.

The strand grid approach is a flow solution method where a prismatic-like grid using 'strands' is grown to a short distance from the body surface to capture the viscous boundary layer and the rest of the domain is covered using an adaptive Cartesian grid. The approach offers several advantages in terms of nearly automatic grid generation and adaptation, ability to implement fast and efficient flow solvers that use structured data in both the strand and Cartesian grids, and the development of an efficient and highly scalable domain connectivity algorithm. An earlier work by the authors introduced a strand grid solver called mStrand, which will appear in future versions of the HPCMP CREATE(TM)-AV Helios framework. This paper presents application of mStrand/Helios grid framework for complex rotorcraft problems. The test cases presented are the UH-60A high speed forward flight and high-altitude stall problems as well as the HART II blade-vortex interaction problem. The results show that the solution obtained using the strand grid framework is as good as that obtained using well-established structured and unstructured solution methodologies.

Lamar, J.

"A CAREER IN VORTICES AND EDGE FORCES"

The Aeronautical Journal, Vol. 116, No. 1176, February 2012, pp. 101-152.

This lecture recognizes the background and distinguished work of Frederick William Lanchester, and notes that my background has a few similarities with his. These include a shared interest in wings, lift and vortices. My career at the NASA Langley Research Center spans the time-frame from America's Super Sonic Transport through 2009. An early emphasis involved wind-tunnel testing of research aircraft models and the development of computer codes for subsonic aerodynamics of wing planforms. These attached-flow codes were applied to various configurations, including those with variable-sweep, dihedral, and more than one planform in both the analysis- and design-modes. These codes were used to provide a connection between leading-edge forces and the associated additional lift on delta-wings with shed-vortex systems through the leading-edge suction analogy of Edward C. Polhamus. Subsequently, I extended the suction analogy to configurations with side-edges to predict the vortical-flow aerodynamics on complex configurations, including wing-strake combinations. These analysis

codes could also be used in a design-by-analysis mode for configurations with leading-edge shed vortices. Later, I was involved in vortical-flow flight research with the F-106B and the F-16XL aircraft at cruise and maneuver conditions. Associated CFD predictions, generated by me and other members of the RTO/AVT-113 task group, have increased our understanding of the flight flow-physics measured on the F-16XL aircraft.

Lamar, J. E.

"PREDICTION OF VORTEX FLOW CHARACTERISTICS OF WINGS AT SUBSONIC AND SUPERSONIC SPEEDS"

Journal of Aircraft, Vol. 13, No. 7, July 1976, pp. 490-494

The leading-edge suction analogy of Polhamus, which has been successful in the prediction of vortex lift characteristics on wings with pointed tips at subsonic and supersonic speeds, has recently been extended to account for the vortex flow characteristics for wings with side edges. Comparisons of experimental data and other currently used methods with the extended method are made for wings having side edges at subsonic and supersonic speeds. Recent data obtained for a low-aspect-ratio cropped-delta wing with various amounts of asymmetrical tip rake, simulating a roll control device, are also presented.

Lamar, J. E.

"A VORTEX-LATTICE METHOD FOR THE MEAN CAMBER SHAPES OF TRIMMED NONCOPLANAR PLANFORMS WITH MINIMUM VORTEX DRAG"

NASA TN D-8090, June 1976, NASA Langley Research Center, Hampton, VA.

A new subsonic method has been developed by which the mean camber surface can be determined for trimmed noncoplanar planforms with minimum vortex drag. This method uses a vortex lattice and overcomes previous difficulties with chord loading specification. This method uses a Trefftz plane analysis to determine the optimum span loading for minimum drag, then solves for the mean camber surface of the wing, which will provide the required loading. Sensitivity studies, comparisons with other theories, and applications to configurations which include a tandem wing and a wing-winglet combination have been made and are presented.

Lamarre, F. and Paraschivoiu, I.

"EFFICIENT PANEL METHOD FOR VORTEX SHEET ROLL-UP"

Journal of Aircraft, Vol. 29, No. 1, January-February 1992, pp. 28-33

In order to improve the accuracy of a potential flow three-dimensional wing panel method, wake deformation must be considered. This leads to a better knowledge of the large-scale flow behavior. In this paper, a computational method modeling the vortex sheet behind a wing is presented. The sheet deformation is computed using a two-dimensional unsteady analogy in the crossflow plane. The local

velocities are induced by linear vorticity panels with smoothed velocity fields. The sheet is re-discretized at each time step with an adaptive curvature-dependent paneling scheme. The vortex sheet model produces good results for the typical cases of elliptic loading, wing/flap configuration, and ring wing. Coupling of the wake model with a three-dimensional wing panel method gives wake geometries that compare well with those obtained with other codes.

Lambourne, N. C.

"THE BREAKDOWN OF CERTAIN TYPES OF VORTEX"

ARC-C-915, September 1965, Aeronautical Research Council, London, England. (Also, NPL-AERO-1166 and ARC-27200.)

Two observed forms of vortex breakdown are compared and experimental evidence is presented to suggest that the spiral form is a derivative of the axisymmetric form. Theoretical examination of the effect of an imposed adverse pressure gradient on a vortex core shows that drastic changes of flow structure must occur when certain critical conditions are exceeded. The theoretical predictions are to some extent consistent with the observed breakdown.

Lambourne, N. C. and Bryer, D. W.

"THE BURSTING OF LEADING-EDGE VORTICES - SOME OBSERVATIONS AND DISCUSSIONS OF THE PHENOMENON"

ARC-22775, April 1961, Nat. Phys. Lab., Great Britain. (Also, ARC R&M-3282.)

Bursting refers to the abrupt structural change from a regular spiral motion to a weaker turbulent motion which can occur at some position along a vortex generated by a sweptback leading edge of a wing. The phenomenon is examined by flow visualization, its sensitivity to several factors is investigated and the reasons for its occurrence are discussed. The burst is found to be sensitive to several factors, in particular, an increase of pressure gradient along the vortex seems conducive to the occurrence of a burst. It is suggested that a condition essential for the burst to occur is a low total pressure within the vortex core coupled with an adverse pressure gradient along the axis.

Lampe, T., Sedin, Y. and Weinerfelt, P.

"FLIGHT TEST VERIFICATION OF A WAKE VORTICES MODEL"

RTO-MP-SCI-162, 2005, Paper 4. Neuilly-sur-Seine, France

A simulation model for encounters of wake vortices has been developed at Saab in Linköping, Sweden. Distribution of incremental forces on the aircraft surfaces is calculated for different locations related to the vortices and also for different relative attitudes of the aircraft. Also, the response of the angle-of-attack and angle-of-sideslip vanes is calculated. For simulation, multidimensional tables are created describing the increments in forces, moments and vane angles as function of relative position and attitude. The model, represented by table lookup algorithms for these particular tables as well as some

scaling algorithms, was in the year 2000 added to an experimental version of a 6-DOF Gripen simulator. The results seemed promising because the response of the aircraft flying through the vortices was, seen from a pilot's view, realistic. However, it was evident that the model also needed to be verified with and, most likely, adjusted (scaled) to flight test data. The need for accurate estimates of the aircraft's trajectory through the vortices requires special attention. Regardless of the ability to accomplish that accuracy in relative position between two aircraft, we still have to determine, also very accurately, where the vortices are, regarding cores and size. Local wind fluctuations and the self-induced motion of the vortices away from the flight path contribute with uncertainties in the range of a couple of meters. From that standpoint, we have too large uncertainties. Our best solution so far is to use a closed-loop verification of the model where we use a subset of the output parameters to identify a two-dimensional position bias that gives us the most likely trajectory. We use the angle-of-attack and angle-of-sideslip vane signals for that purpose. The result is not only a method for verification of a trailing vortex simulation model but also a tool to map out in detail where we have been in wake vortex penetration tests. With respect to the simplifying assumptions used in the design of the current model, the agreement with flight test data is surprisingly good.

Landa, T., Klug, L., Radespiel, R., Probst S. and Knopp, T.

"EXPERIMENTAL AND NUMERICAL ANALYSIS OF A STREAMWISE VORTEX DOWNSTREAM OF A DELTA WING"

AIAA Journal, Vol. 58, No. 7, July 2020, pp. 2857-2868.

The present paper analyzes the vortical flow downstream of a delta wing. The delta wing is designed to generate a vortex that resembles the vortex of a nacelle strake. The experimental results of stereoscopic particle image velocimetry measurements performed at different positions downstream of the delta wing display the streamwise development of the vortex. Details of the postprocessing of the measurement data and a quantification of the uncertainties are presented. The evaluation of the mean axial and tangential velocity components and Reynolds stresses provides insights to the vortex characteristics and their development in the streamwise direction. In addition, results of numerical simulations with the DLR TAU-code applying the Menter-Shear Stress Transport (SST) eddy viscosity model and the Speziale-Sarkar-Gatski/Launder-Reece-Rodi (SSG/LRR)-Omega Reynolds stress model show the ability of the turbulence models to capture the vortex development. The experimental results indicate a preservation of the vortex strength and structure downstream of the delta wing. The Menter-SST model does not predict this preservation; rather it computes a rapid decay of vortex strength and an increase in vortex size. In contrast, the results of the SSG/LRR-Omega model are in good agreement with the experiments concerning the mean flow development. However, both turbulence models underpredict the turbulence in the vortex core.

Landa, T., Klug, L., Radespiel, R., Probst, S. and Knopp, T.

"EXPERIMENTAL AND NUMERICAL ANALYSIS OF A STREAMWISE VORTEX DOWNSTREAM OF A DELTA WING"

AIAA Paper 2018-4157, June 2018, Atlanta, GA.

The present paper analyzes the vortical flow downstream of a delta wing. The delta wing is designed to generate a vortex which resembles the vortex of a nacelle strake. The experimental results of stereo-PIV measurements performed at different positions downstream of the delta wing display the streamwise development of the vortex. The distributions of the mean axial and tangential velocity components and Reynold-stresses characterize the vortex development. In addition, results of numerical simulations with the DLR TAU-code applying the Menter-SST eddy viscosity model and the SSG/LRR-w Reynolds-Stress model show the ability of the turbulence models to capture the vortex development. The experimental results indicate a preservation of the vortex strength and structure downstream of the delta wing. The Menter-SST model does not predict this preservation, rather it computes a rapid decay of the vortex strength and an increase of the vortex size. In contrast, the results of the SSG/LRR-w model are in good agreement with the experiments concerning the mean flow development. However, turbulence in the vortex core is underpredicted by both turbulence models.

Landahl, M. T. and Widnall, S. E.

"VORTEX CONTROL"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 137-155

The fluid dynamical aspects of the control of free vortices emanating from the wing or other parts of a flight vehicle are reviewed. Simple calculations based on slender-body theory are used to demonstrate the importance of controlling the strength, position and core stability and thickness of such vortices. From the equations describing vortex motion, conclusions are drawn as to how vortex properties can be influenced. Simple energy arguments are used to clarify the phenomenon of vortex bursting and to draw conclusions as to what can be done to prevent or induce bursting.

Landgrebe, A. J.

"AN ANALYTICAL METHOD FOR PREDICTING ROTOR WAKE GEOMETRY"

AIAA Paper 1969-196, February 1969, Atlanta, GA.

An analytical method for predicting the distorted geometry of a helicopter rotor wake is described. The development of this method is ultimately directed toward proving a more accurate aerodynamic theory for computing the instantaneous rotor flow field and associated blade airloads. It is shown that: (1) realistic self-induced distortions of a rotor wake represented by numerous discrete vortex elements can be computed by application of the classical Biot-Savart law and numerical integration techniques and (2) by dividing the wake into a series of near and far wake regions, the computation requirements which have previously prohibited the use of such an analysis as a cost-effective engineering tool can be appreciably reduced. Sample comparisons of analytical and experimental wake geometries of a rotor in forward flight are presented and indicate the ability of the analysis to predict the characteristic distortion features of the wake.

Landgrebe, A. J.

"NEW DIRECTIONS IN ROTORCRAFT COMPUTATIONAL AERODYNAMICS RESEARCH IN THE U.S."

Aerodynamics and Aeroacoustics of Rotorcraft, AGARD-CP-552, August 1995, pp. 1-1 to 21-12.

Recent research activities in the United States are presented that are representative of the directions of research for computational aerodynamics for rotorcraft. Emphasis is given to Navier-Stokes methodology for airflow and airload prediction, and specifically the fundamental technical challenges associated with grid systems and achieving wake generation without numerical diffusion. Although the current rotorcraft CFD methods have not yet generally demonstrated sufficient accuracy for the helicopter industry, the recent rate of progress is encouraging.

Landgrebe, A. J.

"AN ANALYTICAL METHOD FOR PREDICTING ROTOR WAKE GEOMETRY"

J. Am. Helicopter Society, Vol. 14, No. 4, October 1968, pp. 20-32.

An analytical method for predicting the distorted geometry of a helicopter rotor wake is described. The development of this method is ultimately directed toward proving a more accurate aerodynamic theory for computing the instantaneous rotor flow field and associated blade airloads. It is shown that: (1) realistic self-induced distortions of a rotor wake represented by numerous discrete vortex elements can be computed by application of the classical Biot-Savart law and numerical integration techniques and (2) by dividing the wake into a series of near and far wake regions, the computation requirements which have previously prohibited the use of such an analysis as a cost-effective engineering tool can be appreciably reduced. Sample comparisons of analytical and experimental wake geometries of a rotor in forward flight are presented and indicate the ability of the analysis to predict the characteristic distortion features of the wake.

Landgrebe, A. J.

"THE WAKE GEOMETRY OF A HOVERING HELICOPTER ROTOR AND ITS INFLUENCE ON ROTOR PERFORMANCE"

28th Annual Forum, American Helicopter Association, Washington, DC, May 1972

Systematic model rotor performance and wake geometry data were acquired to evaluate the influence of wake geometry on rotor hover performance. Analysis of the wake data resulted in (1) the development of a simple generalized representation of the near wake which facilitates the rapid estimation of realistic wake geometries for a wide range of rotor designs and operating conditions and (2) the discovery of a reduction in wake stability with increasing distance from the rotor. The results of a theoretical method for predicting the wake geometry are also presented. Results of a prescribed wake analysis for predicting rotor hovering performance show that the incorporation of a realistic wake

geometry provides significantly improved predictions of rotor performance characteristics. Finally, initial results of advanced experimental techniques for determining rotor wake characteristics are presented along with a brief discussion of other current efforts at UARL pertaining to rotor wake geometry and performance.

Landgrebe, A. J.

"AN ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF HELICOPTER ROTOR HOVER PERFORMANCE AND WAKE GEOMETRY CHARACTERISTICS"

Report 0538827, June 1971, United Aircraft Research Labs., East Hartford, CT.

An analytical and experimental investigation was conducted to acquire systematic model rotor performance and wake geometry data and to evaluate the accuracy of various analytical methods in predicting the effects on performance of changes in helicopter rotor design and operating parameters. Both classical hover performance analyses and analytical methods recently developed at the United Aircraft Research Laboratories were evaluated. Of primary concern in the study was the assessment of assumptions in the analyses regarding the geometry of the rotor wake. Of particular interest was the prediction by the analyses of an instability of the tip vortex helix at moderate distances from the rotor which appeared to be substantiated by available experimental results.

Landgrebe, A. J. and Bellinger, E. D.

"AN INVESTIGATION OF THE QUANTITATIVE APPLICABILITY OF MODEL HELICOPTER ROTOR WAKE PATTERNS OBTAINED FROM A WATER TUNNEL"

USAAMRDL Tech Report 71-69, Dec. 1971, United Aircraft Corp. Research Laboratories, East Hartford, CT.

An analytical investigation was conducted to evaluate quantitative applications of available model rotor tip vortex patterns from a water tunnel. This evaluation consisted of reducing selected photographic wake data to coordinate form, and comparing the resulting wake geometries with both theoretical results and available experimental data taken in air. Additionally, the study included an examination of the sensitivity of water tunnel wake geometry to the water tunnel test parameters which did not duplicate full-scale rotor values and the applicability of a water tunnel wake geometry to determine the airloads of a full-scale rotor. Finally, the possibility of developing simplified wake documentation and generalization procedures and improved water tunnel test techniques was assessed.

Landgrebe, A. J. and Cheney Jr, M. C.

"ROTOR WAKES -- KEY TO PERFORMANCE PREDICTION"

Symposium on Status of Testing and Modeling Techniques for V/STOL Aircraft, Mideast Region of the American Helicopter Society, October 1972, Easington, PA.

The history of helicopter performance prediction methods and the influence of rotor wakes are traced from the simple momentum techniques used in the early years of propellers and rotors to the current state-of-the-art computer programs simulating the rotor's complex vortex structure. Early methods became inadequate as disc loadings increased and wake effects became increasingly important, particularly for hovering and low forward speed conditions where the tip vortex could induce stall at critical points on the blades. Analytical and experimental techniques are described which define the geometry of the vortex field of a hovering rotor and its effect on rotor performance. It was concluded that the most important factor which influences the prediction of hover performance was the interference caused by the tip vortex during its first revolution. Integrated performance in forward flight was generally not sensitive to variable inflow; however, when combined with unsteady airfoil data, variable inflow produced significant effects on blade torsional responses.

Landgrebe, A. J. and Egolf, T. A.

"ROTORCRAFT WAKE ANALYSIS FOR THE PREDICTION OF INDUCED VELOCITIES"

USAAMRDL-TR-75-45, January 1976, United Technologies Research Center, East Hartford, CT

A rotorcraft wake analysis for computing flow velocities induced by the rotors and wing of a helicopter is described, and predicted induced velocities are compared with experimental data from many sources. Combined in a single computerized analysis are the capabilities for calculating three components of time-averaged and instantaneous induced velocities on or off the rotor(s) of single-rotor, dual-rotor, and winged helicopter configurations, in hovering and forward flight.

Landgrebe, A. J., Taylor, R. B., Egolf, T. A. and Bennett, J. C.

"HELICOPTER AIRFLOW AND WAKE CHARACTERISTICS FOR LOW SPEED AND HOVERING FLIGHT FROM ROCKET INTERFERENCE INVESTIGATIONS"

37th Annual Forum, American Helicopter Society, New Orleans, LA, May 1981

With the development of laser velocimetry, specialized flow visualization techniques, and analytical wake methods, measurement and prediction of detailed helicopter airflow and wake characteristics have become feasible. This was demonstrated in a series of experimental and analytical research programs directed toward the investigation of the airflow at selected rocket trajectory, wind sensor, and rotor wake locations of a model helicopter simulating hover and low speed flight conditions. Considering the current increased interest in low speed, low level flying, results of these investigations are presented to provide insight into the airflow and wake characteristics associated with hover and low speed flight near and away from the ground. It is the intent of this paper to present demonstrations of the advanced experimental and analytical techniques employed, and to provide selective rotor wake and airflow velocity information, to contribute to the understanding of the aerodynamics of low-speed helicopter flight. Laser velocimeter and flow visualization data are

presented and compared with theory to provide indications of the influence of airspeed, flight direction, fuselage presence, thrust level, ground effect, and blade-vortex interaction on rotor airflow velocities and wake geometry. The blade-vortex interaction data present significant implications for helicopter low speed performance, vibrations, aerodynamic interference, and noise.

Landgrebe, A. J., Taylor, R. B., Egolf, T. A. and Bennett, J. C.

"HELICOPTER AIRFLOW AND WAKE CHARACTERISTICS FOR LOW SPEED AND HOVERING FLIGHT"

J. American Helicopter Society, Vol. 27, No. 4, October 1982, pp. 74-83

With the development of laser velocimetry, specialized flow visualization techniques, and analytical wake methods, measurement and prediction of detailed helicopter airflow and wake characteristics have become feasible. This was demonstrated in a series of experimental and analytical research programs directed toward the investigation of the airflow at selected rocket trajectory, wind sensor, and rotor wake locations of a model helicopter simulating hover and low speed flight conditions. Results of these investigations are presented to provide insight into the airflow and wake characteristics associated with hover and low speed flight near and away from the ground. Laser velocimeter and flow visualization data are presented and compared with theory to provide indication of the influence of airspeeds, flight direction, fuselage presence, thrust level, ground effect, and blade-vortex interaction on rotor airflow velocities and wake geometry and to demonstrate theory-test correlation.

Landman, M. J. and Saffman, P. G.

"THE THREE-DIMENSIONAL INSTABILITY OF STRAINED VORTICES IN A VISCOUS FLUID"

Physics of Fluids, Vol. 30, No. 8, August 1987, pp. 2339-2342.

The recent theory describing 3-D exact solutions of the Navier-Stokes equations is applied to the problem of stability of 2-D viscous flow with elliptical streamlines. An intrinsically inviscid instability mechanism persists in all such flows provided the length scale of the disturbance is sufficiently large. Evidence is presented that this mechanism may be responsible for 3-D instabilities in high Reynolds number flows whose vortex structures can be locally described by elliptical streamlines.

Landry, S. J. and Jacko, J.

"PILOT PROCEDURE-FOLLOWING BEHAVIOR DURING CLOSELY SPACED PARALLEL APPROACHES"

International Journal of Human-Computer Interaction, Vol. 28, No. 2, 2012, pp. 131-139.

A flight simulator experiment was run to examine pilot procedure-following behavior during closely spaced parallel approaches. Such approaches are being considered under the Next Generation Air Transportation System (NextGen) to increase the capacity of runway systems, possibly without the need to increase the footprint of airports. Pilots flying these approaches utilized a simple heuristic to fly the procedure consistently, despite the heuristic being suboptimal for any of the three conditions.

Moreover, procedure compliance was relatively low, but noncompliance itself was not unsafe unless accompanied by situation awareness problems. In some cases, noncompliance could be shown to be a better choice than compliance. These results have implications for assumptions regarding procedure-following by pilots utilizing novel procedures in NextGen.

Landry, S. J. and Lynam, A.

"SAFE ZONE FOR CLOSELY SPACED PARALLEL APPROACHES"

Journal of Guidance, Control, and Dynamics, Vol. 34, No. 2, March-April 2011, pp. 608-613.

A safe zone can be computed that provides protection against blunders for a predetermined period of time. This safe zone has a reasonable width under most conditions, and adhering to the safe zone should improve capacity over current methods for closely spaced parallel approaches. The safe zone is influenced by the time needed for responding to an alert, the speed difference between two aircraft, the lateral separation between the paths of the aircraft, and the crosswind speed. Greater speed differences, larger speed differences, and wider lateral separations result in more distant in-trail separations. Higher crosswind speeds reduce the width of the safe zone. A practical safe zone exists up to approximately 40 kt different in speed and 40 kt crosswind for runways, down to 750 ft lateral separation. Implementing the safe zone, while reducing capacity when compared with independent operations, has a significant improvement over current operations. The guidance can be applied to current visual approaches, without the addition of any instrumentation, to improve the safety of those approaches without substantially impacting capacity. If a depiction is provided on a primary or secondary flight instrument, the safe zone may allow for closely spaced parallel approaches in instrument conditions to runways down to 750 ft lateral separation.

Landry, S. J. and Pritchett, A. R.

"INCORPORATING PROCEDURAL INFORMATION IN A PAIRED APPROACH PAIR"

Proceedings of the Human Factors and Ergonomics Society, 46th Annual Meeting, October 2002, Baltimore, MD, pp. 106-110.

This study focused on pilot performance at simultaneously flying simulated instrument approaches and self-separating from an aircraft on approach to a closely spaced parallel runway. The participant pilots flew approaches on Georgia Tech's Reconfigurable Flight Simulator and were instructed to remain within the 'safe zone' -- an area in which the subject aircraft was safe from collision danger and wake vortices from the other aircraft -- as depicted on their navigation display. Two underlying bases for calculating the safe zone were used: a 'predicted' safe zone utilizing procedural information, and an 'actual' safe zone utilizing real-time information. No display effects were found for pilot performance or behavior, despite the very different implications of the two safe zone depictions. Also, pilots monitored the other aircraft closely for compliance, but could not recognize the implications of noncompliance for their own approach. This suggests that pilots have a particular, persistent, and perhaps poor, strategy for this task.

Lane, S. E., Barlow, J. F. and Wood, C. R.

"AN ASSESSMENT OF A THREE-BEAM DOPPLER LIDAR WIND PROFILING METHOD FOR USE IN URBAN AREAS"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 119, 2013, pp. 53-59.

Currently there are few observations of the urban wind field at heights other than rooftop level. Remote sensing instruments such as Doppler lidars provide wind speed data at many heights, which would be useful in determining wind loadings of tall buildings, and predicting local air quality. Studies comparing remote sensing with traditional anemometers carried out in flat, homogeneous terrain often use scan patterns which take several minutes. In an urban context the flow changes quickly in space and time, so faster scans are required to assure little change in the flow over the scan period. We compare 3993 h of wind speed data collected using a three-beam Doppler lidar wind profiling method with data from a sonic anemometer (190 m). Both instruments are located in central London, UK; a highly built-up area. Based on wind profile measurements every 2 min, the uncertainty in the hourly mean wind speed due to the sampling frequency is 0.05-0.11 m/s. The lidar tended to overestimate the wind speed by about 0.5 m/s for wind speeds below 20 m/s. Accuracy may be improved by increasing the scanning frequency of the lidar. This method is considered suitable for use in urban areas.

Lane, S. E., West, L. L., Gimmetstad, G. G., Smith Jr, W. L. and Burdette, E. M.

"DETECTION OF AIRCRAFT EXHAUST IN HYPERSPECTRAL IMAGE DATA"

Proceedings SPIE, Vol. 8158, Imaging Spectrometry XVI, September 2011, pp. 815800-1 - 815800-8.

The use of a hyperspectral imaging system for the detection of gases has been investigated, and algorithms have been developed for various applications. Of particular interest here is the ability to use these algorithms in the detection of the wake disturbances trailing an aircraft. A dataset of long wave infrared (LWIR) hyperspectral datacubes taken with a Telops Hyper-Cam at Hartsfield-Jackson International Airport in Atlanta, Georgia is investigated. The methodology presented here assumes that the aircraft engine exhaust gases will become entrained in wake vortices that develop; therefore, if the exhaust can be detected upon exiting the engines, it can be followed through subsequent datacubes until the vortex disturbance is detected. Gases known to exist in aircraft exhaust are modeled, and the Adaptive Coherence/Cosine Estimator (ACE) is used to search for these gases. Although wake vortices have not been found in the data, an unknown disturbance following the passage of the aircraft has been discovered.

Lane, T.

"PROCESSES UNDERLYING NEAR-CLOUD TURBULENCE"

In *Aviation Turbulence*, edited by R. Sharman and T. Lane, Chapter 16, 2016, Springer International Publishing Switzerland, pp. 317-334.

Thunderstorms generate turbulence both within cloudy air and in the clear air surrounding them. Both in-cloud and out-of-cloud turbulence are an aviation hazard, and the latter can pose a risk of unexpected encounters because it is invisible and is unable to be detected using standard on-board radar technology. In recent years there has been a significant improvement in the understanding of out-of-cloud turbulence generation mechanisms, including identifying the importance of breaking atmospheric gravity waves. In this chapter, numerical modelling studies are used to explain the processes leading to turbulence outside of cloud, including near the cloud boundary and above storms. Turbulence near the cloud boundary is explained by local instabilities associated with storm-induced wind shear. Turbulence further aloft is related to gravity wave breaking that is well explained by linear theory. Very high-resolution simulations are also used to quantify the intensity of turbulence and how it varies spatially. These simulations demonstrate that, although the main convective regions of storms possess the most intense turbulence, notable regions of turbulence can extend significant distances vertically and horizontally from the cloud boundary.

Lang, S.

"STL DATA COLLECTION CAMPAIGN - STATUS AND ANALYSIS PLANS"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

The FAA and NAS are jointly investigating wake turbulence avoidance strategies for eventual implementation into the National Airspace System (NAS). They have jointly developed a phased approach to increase airport capacity through safe reduction of existing wake turbulence constraints. The objective of the first phase of the program is the development of procedural wake avoidance solutions for CFSR airports and is led by the FAA. The objective of the second phase of the program is the development of wind-dependent procedures for wake avoidance that include wind prediction algorithms and simple controller tools to support decision making. This phase also targets CFSR airports and is led jointly by the FAA and NASA. The objective of the third phase of the program is the development of active wake avoidance solutions including technologies for wake prediction and monitoring and is led by NASA. In the first phase of the program, the FAA is seeking to make a near-term change to the 2500-foot rule for CFSR arrivals to define a lesser runways centerline separation minimum for avoidance of wakes generated by Small-and-Large aircraft. The objective is to permit today's dependent (1.5 NM diagonal separation) CFSR approach procedures between Large-and-Small aircraft and for any type aircraft trailing a Large or Small leading aircraft on the parallel runway. The first data collection and analysis campaign for this effort is being conducted at STL. This campaign is designed to support the safety assessments to be conducted by the FAA's Flight Standards organization in support of the procedure change.

Lang, S. R., Tittsworth, J. A., Lepadatu, C., Delisi, D. P., Lai, D. Y. and Greene, G. C.

"PROGRESS ON JOINT FAA/EUROCONTROL EFFORT TO DEVELOP AN ICAO WAKE TURBULENCE RE-CATEGORIZATION"

8th USA/EUROPE Air Traffic Management Research & Development Seminar, June/July 2009, Napa, CA.

Planned improvements in Air Traffic Management, as described by NextGen in the US and SESAR in Europe, have a common goal of enhancing capacity and harmonizing separation standards. Wake vortices are a product of lift from aircraft and are one of the major constraints in the reduction of separation standards that are one of the solution avenues that NextGen and SESAR are pursuing in the goal for increased capacity. The existing separation standards based on wake turbulence are significantly different between the US and ICAO. Furthermore, both the ICAO and US categories, and associated separation minima among the categories, represent two very safe systems but are optimized for fleet mixes that existed 15 or more years ago. As an example, the last re-categorization effort in the US was performed in 1994. Better knowledge of wake behavior obtained through research and improved sensors that measure wake turbulence provide an opportunity to develop a new set of common categories that provide the same or increased safety over the existing US and ICAO categories while optimizing for current and future traffic demands in the US and Europe. This paper describes a joint FAA/EUROCONTROL methodology for developing and evaluating new candidate wake turbulence categories. The paper provides examples and rough estimates of capacity gains that some examples show over today's US and ICAO categories. Finally, the paper highlights the key steps yet to be completed in achieving a joint recommendation to ICAO in 2010.

Lang, S., Domino, D. A., Mundra, A. and Bodoh, C.

"ATC FEASIBILITY OF POTENTIAL NEAR-TERM WAKE TURBULENCE PROCEDURES"

23rd Digital Avionics Systems Conference, Vol. 1, Oct. 2004, pp. 5.B.4-1-5.B.4-15

This paper documents the results of controller (human-in-the-loop, HITL) simulations to evaluate a proposed change of standards involving the wake turbulence separation required for closely spaced parallel runways with center line separation less than 2500 feet. Under current rules, dependent, diagonal separation between arrivals on adjacent parallel runways can be used when runway center line separation is at least 2500 ft. The Federal Aviation Administration is investigating the reduction of this required minimum runway separation value to 1000 ft. when the leading airplane is in the Large-or-Small weight category. If the lead aircraft is a B-757 or Heavy then standard wake turbulence separation would apply. This change would enable continued operation of dual arrival streams in instrument conditions, increasing airport capacity and reducing delay. Real time simulations were conducted with controllers from a busy U.S. ATC facility to determine if such a change in standard would be acceptable and feasible. Both approach control and tower control positions were simulated. Results indicate that ATC operations with the proposed new standards were feasible, controller workload was acceptable as measured in the simulation environment, and that significant capacity benefits may be achieved both for arrivals and departures in instrument meteorological conditions (IMC) for such runway geometries. The paper includes a discussion of the procedures and strategies developed by the controllers in implementing the proposed change in standards, and presents results regarding controller workload, achieved arrival and departure rates, and various spacing values of

interest on final approach relevant to a safety analysis of the procedure. The paper also suggests some steps that may help develop authorization of such a procedure.

Lang, S., Mundra, A. D., Cooper, Jr. W. W., Levy, B. S., Lunsford, C. R., Smith, III, A. P. and Tittsworth, J. A.

"A PHASED APPROACH TO INCREASE AIRPORT CAPACITY THROUGH SAFE REDUCTION OF EXISTING WAKE TURBULENCE CONSTRAINTS"

Air Traffic Control Quarterly, Vol. 11, No. 4, 2003, pp. 331-356

Previous wake turbulence research has suggested that using knowledge of wake turbulence behavior to develop candidate arrival and departure procedures would increase capacity at a variety of US airports. This paper outlines the operational issues involved as well as the process through which the Federal Aviation Administration (FAA) and The MITRE Corporation's Center for Advanced Aviation System Development analyzed an evolving set of candidate procedures. This work is part of the broader effort to implement an FAA/National Aeronautics and Space Administration Wake Turbulence Research Management Plan. We describe in detail two candidate procedures, their operational variations, and the expected capacity benefits at selected airports. The first procedure is a near-term proposed change to the 2500-foot runway centerline separation minimum for dependent approaches to two closely spaced parallel runways. When visual separation cannot be provided, the current FAA rule requires parallel runways spaced less than 2500 ft. to be treated as a single runway. While in-trail wake separation standards are dependent on wake categories of the generating and encountering aircraft, this rule is not. This paper shows that, by refining this standard to reflect the wake generation differences of different weight classes, substantial capacity benefits may be possible. Variations on this procedure are analyzed to explore the sensitivity of the capacity benefits to the underlying assumptions. The second procedure is a mid-term proposed change to reduce wake constraints for departures from parallel runways spaced closer than 2500 ft. using a short-term prognosis of crosswinds at and near the area of aircraft rotation. A brief outline is provided of activities planned during 2004 to advance towards the specific design and implementation of these procedures. One such activity is additional wake data collection at St. Louis.

Lang, S., Mundra, A. D., Cooper, Jr., W. W., Levy, B. S., Lunsford, C. R., Smith, III, A. P. and Tittsworth, J. A.

"A PHASED APPROACH TO INCREASE AIRPORT CAPACITY THROUGH SAFE REDUCTION OF EXISTING WAKE TURBULENCE CONSTRAINTS"

Fifth EUROCONTROL/FAA ATM R&D Seminar, June 2003, Budapest, Hungary

This paper outlines the operational issues involved in using knowledge of wake turbulence behavior to develop candidate terminal approach procedures that would increase arrival capacity at a variety of United States airports. Later procedures build incrementally on the experience that would be gained with these initial procedures. The process by which the Federal Aviation Administration (FAA) and The Mitre Corporation's Center for Advanced Aviation System Development (MITRE/CAASD) have been analyzing these candidate procedures will be discussed. This process is part of the broader effort to

implement an FAA/National Aeronautics and Space Administration (NASA) Wake Turbulence Research Management Plan (RMP). Two candidate procedures, and their operational variations, are described in detail, along with expected capacity benefits at selected airports. The analysis methodology is described. The first procedure is a near-term proposed change to the 2500-foot separation minimum for dependent approaches to two parallel runways. The second procedure is a mid-term proposed change to reduce wake constraints for departures from parallel runways spaced closer than 2500 feet using a short-term prognosis of crosswinds at and near the area of aircraft rotation. Activities, such as additional wake data collection at a field site, that are planned during the current year to advance towards the specific design and implementation of the procedures are also briefly outlined.

Lang, S., Tittsworth, J. A., Lunsford, C. R., Cooper, W. W., Audenaerd, L., Sherry, J. and Cole, R. E.

"AN ANALYSIS OF POTENTIAL CAPACITY ENHANCEMENTS THROUGH WIND DEPENDENT WAKE TURBULENCE PROCEDURES"

6th USA/Europe Air Traffic Management Research and Development Seminar, June 2005, Baltimore, MD.

The Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) are jointly embarking on a multi-phased research and development program to develop and implement wake avoidance solutions that can safely reduce separations and improve capacity at airports in the National Airspace System (NAS). The mid-term phase of the research focuses on the potential application of wind-dependent procedures for improved departure operations from Closely Spaced Parallel Runways (CSPR) in the U.S. This paper describes the research performed to date by a few members of the larger research team, including the FAA, Lambert St. Louis International Airport operational staff, MIT Lincoln Laboratory and MITRE Center for Advanced Aviation System Development (CAASD). It describes the operational concept, the wind prediction algorithms being developed to support this concept, and an analysis of expected algorithm performance. In addition, this paper addresses the information requirements for a decision support tool to support this procedure and the potential benefits that may be realized by this procedure at several CSPR airports in a weather and traffic demand environment. NASA is in early stages of extending this wind-dependent solution for other operations such as single runway departures. The paper also describes the thrust of these evolutionary concepts and the directions of research.

Lang, S., Tittsworth, J., Bryant, W. H., Wilson, P., Lepadatu, C., Delisi, D. P., Lai, D. Y. and Greene, G. C.

"PROGRESS ON AN ICAO WAKE TURBULENCE RE-CATEGORIZATION EFFORT"

AIAA Paper No. 2010-7682, August 2010, Toronto, Canada.

This paper describes progress on an ICAO tasking to the FAA and Eurocontrol to lead an effort to harmonize wake turbulence separation standards for existing and new aircraft and to safely increase capacity. The first phase of the re-categorization effort looked at placing the existing traffic mix of both the U.S. and Europe into 6 categories. The second phase of the effort will determine static pair-wise

spacing that will work for all atmospheric conditions. The final phase of re-categorization will provide dynamic pair-wise spacing that will vary with atmospheric conditions and aircraft performance. This paper provides the methodology of the first phase of re-categorization and gives examples of new aircraft categories that show capacity increases over today's U.S. and ICAO categories.

Lang, S., Tittsworth, J., Domino, D., Lunsford, C., Clark, D., Robasky, F. and Lohr, G.

"WAKE TURBULENCE MITIGATION FOR DEPARTURES FROM CLOSELY SPACED PARALLEL RUNWAYS: A RESEARCH UPDATE"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-176, September 2007, pp. 3371-3381

The Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) have embarked on a multi-phased research and development program to develop and implement wake avoidance solutions that can safely reduce separation between aircraft and improve capacity at airports in the United States National Airspace System (NAS). The mid-term phase of the research focuses on the application of wind-dependent procedures for improved departure operations from Closely Spaced Parallel Runways (CSPRs) in the U.S. These procedures are referred to collectively as Wake Turbulence Mitigation for Departures (WTMD). This paper reports on recent findings of the joint research performed to date by members of the research team, which includes FAA, Lambert St. Louis International Airport Air Traffic Control operational staff, Massachusetts Institute of Technology (MIT) Lincoln Laboratory, MITRE Center for Aviation System Development (CAASD), NASA Langley Research Center, and the Volpe National Transportation Systems Center. In this paper, we review the WTMD concept, including potential benefits that may be derived from its use, report on the most recent work in the development of wind forecast algorithm, provide results of a recent simulation study of controller use of the new procedures, and conclude with a description of the initial prototype installation and validation of controller information requirements.

Langweil, L.

"WAKE VORTEX AVOIDANCE SYSTEM PROGRAM"

Flight in Turbulence, AGARD, CP-140, 1973, pp. 12-1 to 12-9.

The paper describes the Wake Vortex Avoidance System program now being carried out by the FAA. The program's basic objective is to design a predictive system which will increase runway capacity by eliminating the need for the large fixed separations now required between aircraft. These will be replaced by a dynamic safe spacing tailored to the aircraft type and prevailing meteorological conditions. The program consists of three major task areas: sensor development, vortex behavior, hazard definition and the integration of these tasks into an overall system design.

Lanham, C.

"INERTIA CALCULATION PROCEDURE FOR PRELIMINARY DESIGN"

ASD-TR-79-5004, March 1979, Wright-Patterson AFB, Ohio.

This report explains the methods involved in estimating aircraft moments of inertia for preliminary design purposes. Assumptions that were made for this procedure and the derivation of equations that evolved from these assumptions are included. This procedure requires a knowledge of the major aircraft group weights, the location of major components (landing gear, avionics bay, etc.), geometry information, and inertias of some major subsystem items. Using this data, the moments of inertia about the roll, pitch, and yaw axes are calculated as well as the roll-yaw cross-product of inertia.

Lankford, D. N., McCartor, G., Greene, G., Yates, J. and Ladecky, S.

"SAN FRANCISCO INTERNATIONAL AIRPORT SIMULTANEOUS OFFSET INSTRUMENT APPROACH PROCEDURES (SOIA)"

DOT-FAA-AFS-420-84, March 2000, FAA Standards Development Branch, Oklahoma, OK.

This study is based on a United Airlines/Air Line Pilots Association (UAL/ALPA) joint concept of operations proposal that introduces a Simultaneous Offset Instrument Approach (SOIA) procedure with an ILS straight in to runway 28L and an LDA with glide slope and a side step to runway 28R at the San Francisco International (SFO) Airport. Proponents believe an offset LDA with electronic glide slope usable throughout the visual approach segment, a Precision Runway Monitor (PRM) system, Distance Measuring Equipment (DME), and a MAP located 3,000 feet to 3,400 feet abeam of the parallel localizer course will have significantly enhanced flying qualities and provide increased operational efficiency and safety. The Flight Procedure Standards Branch (AFS-420) was asked to evaluate LDA approaches using a 3 deg offset LDA with glide slope; i.e., non-precision instrument approaches, to runway 28R. The proponents have suggested a MAP, denoted LDA_D, from which the visual transition to the landing runway, runway 28R, can be suitably performed by all current air carrier airplanes, including heavy aircraft, such as the Boeing 747-400 while simultaneously approaching with landings to runway 28L. Three test approaches, identified as LDA_A, D, and E, using a 3 deg offset LDA with glide slope and DME were designed and tested using a qualified, level C flight simulator. Statistical analysis indicated that LDA_A and LDA_D, should be the preferred approaches among the three tested and that the criteria for success, as stated in the test plan, were all met or exceeded by LDA_A and LDA_D. Because of the similarity in flyability qualities and the lower minimums provided by LDA_D, LDA_D is the preferred procedure. LDA_D is recommended for implementation with several operational requirements.

Lankford, D., Greene, G., Ladecky, S. and Moore, C.

"CLEVELAND-HOPKINS INTERNATIONAL AIRPORT SIMULTANEOUS OFFSET INSTRUMENT APPROACH WAKE VORTEX EVALUATION "

DOT-FAA-AFS-440-13, August 2005, Flight Operations Simulation and Analysis Branch, Oklahoma City, OK.

This report presents the results of a wake vortex evaluation performed on the proposed CLE SOIA operations. The proposed SOIA operations at CLE incorporate straight-in Instrument Landing System (ILS) approaches to runways 24R and 6L and Localizer-type Directional Aid (LDA) approaches with glide slope to runways 24L and 6R. After the LDA MAP, the SOIA aircraft must perform a lateral maneuver to align with the landing runway. It is during this, the visual segment of the approach, that the landing aircraft get laterally closer to one another and where wake vortex concerns must be addressed. The analysis shows that the proposed SOIA operation to runways 6L/R at CLE poses no wake turbulence hazard. Thus, any and all aircraft wake turbulence classes (except Heavy) may be paired for the SOIA operation. Unrestricted use of the proposed SOIA operation to runways 24L/R, however, does pose a wake turbulence hazard for the participating aircraft; therefore, in accordance with FAA Order 8260.49, specific wake turbulence mitigation strategies are recommended. The LDA approaches developed for the CLE SOIA were not designed for Heavy wake turbulence class aircraft, therefore, this analysis does not address Heavy aircraft as part of the SOIA operation.

Lankford, D., McCartor, G., Greene, G., Yates, J. and Ladecky, S.

"LAMBERT-ST. LOUIS INTERNATIONAL AIRPORT WAKE VORTEX STUDY FOR RUNWAYS 30L AND 30R"

DOT-FAA-AFS-420-89, November 2001, FAA Standards Development Branch, Oklahoma City, OK.

The Airspace Simulation and Analysis for TERPS system was used to determine the risk of a wake vortex encounter associated with simultaneous operations to runways 30L and 30R at St. Louis Lambert International Airport (STL) using the enhanced ASAT wake vortex model version 1.2. Five sets of 100,000 ASAT runs were executed. Each set of runs was executed at a selected initial in-trail separation distance ranging from 0.5 NM to 2.5 NM at 0.5 NM increments. The runs were executed using the current aircraft fleet mix and conservative wind conditions. A sensitivity analysis was performed to determine whether a high-risk wake vortex encounter window exists and can be defined. The simulation was conducted with a ground level, direct crosswind from the right at 10 KT increasing logarithmically to 20 KT at 2,000 feet. The simulation did not detect a high-risk wake vortex encounter window. This can be attributed to the relative positions of the runways. The runway centerlines are spaced 1,300 feet apart and the thresholds are staggered 1,698 feet. Therefore, an aircraft approaching runway 30L with a 10 KT or less direct crosswind from the right that increases logarithmically to 20 KT at 2,000 feet is unlikely to encounter a wake vortex that was generated by an aircraft approaching runway 30R. The probability of an encounter is not affected by category combination or in-trail separation provided the aircraft approaching 30R leads the aircraft approaching 30L.

Lankford, D., McCartor, G., Ladecky, S. and Moore, C.

"SAFETY STUDY REPORT ON SAN FRANCISCO INTERNATIONAL AIRPORT SIMULTANEOUS OFFSET INSTRUMENT APPROACH (SOIA) WAKE VORTEX RE-EVALUATION"

DOT-FAA-AFS-440-8, April 2005, Flight Standards Service, Oklahoma, OK.

In order to increase capacity at San Francisco International Airport during periods of inclement weather, the FAA has implemented a SOIA operation. The SOIA operation consists of a straight-in Instrument Landing System (ILS) approach to runway 28L and a Localizer Directional Aid (LDA) approach with glide slope to runway 28R. Since the runways in question are separated by only 750 feet, one of the primary safety concerns, as reported in Volume I, was that of wake turbulence. Volume I recommended a wake turbulence mitigation strategy based on the concept of an 'operational window.' The SOIA operation calls for the RWY 28L aircraft to lead and the RWY 28R to trail while approaching to land at SFO. To avoid wake vortex encounters, the trailing aircraft must remain within an 'operational window' behind the leading aircraft. In Volume I, the size of the operational window was determined to be 0.6 NM for a heavy aircraft following a heavy aircraft. Since Volume I was published, actual wake vortex data has been collected and analyzed at SFO runways 28 L and R. This study concludes that the size of the operational window can be increased to approximately 1 NM (depending on the speed of the leading aircraft) based on the SFO wake vortex data collection and analysis.

Lanoix, P.

"PERSPECTIVE OF CANADIAN AIRPORTS COUNCIL"

International Wake Vortex Meeting, Transport Canada, Ottawa, Canada, Dec, 1997

For most Canadian airports, separation on final is not an issue because the demand is not there. For the few airports with high demand, facilities have to be built to cater to those demands. As the demand increases, it is critical to identify any capacity gain that could be acquired through reduced separation on final. Numerous Canadian airports are going through major changes to handle the increased traffic. Planning and building capacity sometimes require long lead times. In addition, environmental constraints can add to the time required to build an extra runway should the demand be there and the present runway capacity not be available. Each airport is a unique environment: traffic demand, local weather, aircraft types, environment, etc. Every airport, therefore, requires to be considered individually when planning to invest in any vortex prediction model or facility.

Laporte, F.

"INSTABILITIES OF WAKE VORTEX MODELS IN THE NEAR AND FAR FIELDS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Ensuring accelerated wake vortex decay under any kind of atmospheric conditions is one of the most promising approaches to the wake vortex problem. Enhanced decay might be obtained by acting on the potential instability mechanisms that are likely to develop in wake vortex systems. The knowledge of the stability properties of the vortex systems shed by aircraft is a necessary pre-requisite to the control of these flows. Near field flows (of downstream extension between 1 and 20 wingspans, orders of magnitude) are modeled by considering a single-flap wing shedding two co-rotating vortices, corresponding to the flap and tip vortices. The stable interaction between these vortices corresponds

to the well-known merging phenomenon resulting in a single stable vortex. The simulations reveal also the possible development of a three-dimensional elliptic instability in these two vortices, confirming and extending the recent discovery of Meunier and Lewke in a low Reynolds number experiment. The instability would lead to an unstable merging resulting in a turbulent final vortex. The characteristics associated to the final vortex are found to be potentially significantly different with or without the instability. Far field flows (of downstream extension larger than 10-20 wingspans) are modeled by considering the wake vortex system shed by an aircraft formed after completion of the roll-up process. For many aircraft types in the fleet, this results in a unique pair of counter-rotating vortices, which can be characterized by a single control parameter. The linear, nonlinear and transitional regimes are simulated in the case of the development of the long-wavelength Crow instability, and in the case of the development of the short-wavelength elliptic instability. The influence of the control parameter on the dynamics is discussed, and the late stages of the flows are characterized in terms of hazard. Potential benefits and disadvantages brought by the use of these instability phenomena to accelerate the vortex decay are detailed. The optimal control conditions for an efficient wake destabilization using these mechanisms are interpretable in terms of wing design.

Laporte, F. and Corjon, A.

"A NUMERICAL STUDY OF THE ELLIPTIC INSTABILITY OF A VORTEX PAIR"

Lecture Notes in Physics, Issue 555, 2000, pp. 190-204

The elliptic instability developing in a laminar vortex pair with a high ratio of the vortex core size to the separation distance between the vortices is studied by direct numerical simulations. The computations allow the prediction of both the linear regime of the instability development and the non-linear regime including the transition to a locally turbulent flow.

Laporte, F. and Hansen, H.

"METHOD OF CONTROLLING AN AIRCRAFT IN FLIGHT, ESPECIALLY TO REDUCE WAKE VORTICES"

US Patent 8,118,263 B2, February 2012.

The flight of an aircraft is controlled by controlling the aircraft propulsion thrust and adjusting aerodynamic control elements so that the aircraft flies along a specified flight path. In order to reduce wake vortices generated by and trailing behind the aircraft, a wake vortex parameter is determined as a function of a spoiler deflection, and a spoiler element is adjusted to a spoiler deflection value in an optimum range in which the spoiler influence on the wake vortex parameter is maximized and the spoiler influence on the aircraft performance is at its lowest level for achieving that maximum spoiler influence on the wake vortex parameter.

Laporte, F. and Hansen, H.

"METHOD OF CONTROLLING AN AIRCRAFT IN FLIGHT, ESPECIALLY TO REDUCE WAKE VORTICES"

US Patent No. 7,874,523 B2, Jan. 2011, Airbus Deutschland, Hamburg, German.

The flight of an aircraft is controlled by controlling the aircraft propulsion thrust and adjusting aerodynamic control elements so that the aircraft flies along a specified flight path. In order to reduce wake vortices generated by and trailing behind the aircraft, a wake vortex parameter is determined as a function of a spoiler deflection, and a spoiler element is adjusted to a spoiler deflection value in an optimum range in which the spoiler influence on the wake vortex parameter is maximized and the spoiler influence on the aircraft performance is at its lowest level for achieving that maximum spoiler influence on the wake vortex parameter.

Laporte, F. and Leweke, T.

"ELLIPTIC INSTABILITY OF COUNTER-ROTATING VORTICES: EXPERIMENT AND DIRECT NUMERICAL SIMULATION"

AIAA Journal, Vol. 40, No. 12, December 2002, pp. 2483-2494

The short-wavelength elliptic instability of a pair of closely spaced counter-rotating vortices is analyzed using water tank experiments and direct numerical simulations. Qualitative and quantitative comparison shows excellent agreement and validates each of these complementary approaches. Both sets of results are used to give a detailed description of the instability characteristics. In the initial phase, the vortices are subject to a three-dimensional perturbation of their internal structure, with a wavelength scaling on the vortex core size and a distinct phase relationship between the two vortices. In the nonlinear evolution of the flow, the growth of the perturbations leads to the generation of secondary vortices and the breakdown of the initial pair into small-scale turbulence, accompanied by a rapid decrease of the average circulation. The growth rate of the instability is found to be higher than the one of the well-known Crow instability. The interaction between both mechanisms is also investigated, and an even faster decay of circulation is observed than for the cases where each instability acts alone. The relevance of these results for realistic aircraft trailing wakes is discussed.

Laporte, F., Darracq, D. and Corjon, A.

"ON THE VORTEX-TURBULENCE INTERACTION: DNS OF ELLIPTIC INSTABILITY OF A VORTEX PAIR"

AIAA Paper No. 1999-3417, Norfolk, VA, June-July 1999

The objective of this study is to perform direct numerical simulations (DNS) of the three-dimensional short-wavelength elliptic instability developing in a counter-rotating vortex pair. The structure of this instability is different from the well-known long-wavelength Crow instability, but interactions between these two instabilities may exist. The aim of the present work is to reproduce numerically a water-tank experiment. The main features of the elliptic instability are recovered by the simulations. In particular, the growth rate of the most amplified wavelength during the first phase of the simulation corresponds to both experimental measurements and linear stability analysis predictions. The long-term evolution is also simulated. The complete simulation starts with a two-dimensional laminar flow and is stopped

when the flow has become three-dimensional and turbulent. The stages leading to transition to turbulence are described.

Larin, A.

"VORTEX WAKE BEHIND A HELICOPTER"

Aviatiya i kosmonavtika, No. 3, 1973, pp. 32-33

Research into the vortex wake behind a helicopter was recently carried out. It was found that vortex cords are cores created behind a helicopter are complex structures and are quite stable. The phenomenon of 'secondary vortex generation' was studied on a model with various numbers of blades.

Larson, R. S. and Robbins, K. W.

"REFRACTION OF SOUND BY AIRCRAFT WING TIP VORTICES"

AIAA Paper No. 1980-0975, Hartford, CT, June 1980.

A detailed study was conducted to define the effect of a wing tip vortex on aircraft flyover noise. The Lamb vortex, the modified Lamb vortex, and a turbulent vortex were three models used to simulate a wing tip vortex. A theoretical geometrical acoustics model was developed to predict the effect of an aircraft's wing tip vortex on acoustic measurements obtained in typical sideline noise tests. Theoretical predictions demonstrated that the refraction and convective amplification effects from a wing tip vortex can cause large distortions in the acoustic field radiated by an engine.

Latham, M.

"APPLICATION CONSIDERATIONS FOR MOSQUITO CONTROL"

International Conf. on Pesticide Application for Drift Management, October 2004, Hawaii, pp. 143-149

Mosquito control aerial adulticiding sprays rely on the drift of aerosol spray clouds with drop sizes less than 50 microns in diameter. These sprays by their very nature will drift for a long distance. To minimize biologically significant off-target drift, careful planning derived from a good understanding of all aspects influencing spray cloud dispersal is essential. Three phases of vertical spray cloud dispersal occur between emission at the aircraft nozzle and depositing out at ground level: entrainment within the descending aircraft vortices, general atmospheric turbulence, and sedimentation. These three phases of movement are influenced by four major factors (assuming aircraft type, speed and weight are constant): Droplet size, Spray altitude, horizontal wind speed and atmospheric stability. For the small drop sizes effective against adult mosquitoes, sedimentation velocity is very small and so sedimentation plays a minimal role in their vertical transport from aircraft to ground level. But it may be important in regards to the larger droplet fraction produced by inefficient 'conventional' spray systems which produce a spray cloud with a VMD between 50 and 100 microns. There is a paucity of research data describing spray cloud movement in mosquito control aerial adulticiding. Advancements in research

equipment such as LIDAR and SODAR may provide the technology to better understand the spray cloud movement and the meteorology in which it occurs. Future research on these subjects must be supported by the mosquito control industry, chemical/equipment manufacturers and the government.

Latorre, R., Muller, A., Billard, J. Y. and Houlier, A.

"INVESTIGATION OF THE ROLE OF POLYMER ON THE DELAY OF TIP VORTEX CAVITATION"

Journal of Fluids Engineering, Vol. 126, September 2004, pp. 724-729.

Cavitation tunnel measurements have shown tip vortex cavitation inception is delayed when polymers are injected from the hydrofoil tip. Experiments with polymers have also shown that the polymers cause the cavitation to become more violent. To better understand the role of polymer in the delay of tip vortex cavitation, a theoretical analysis of tip vortex cavitation inception in pure water and in polymer solution is presented. The analysis shows that while polymer injection causes instability in small bubbles, its main effect is an increase in tip vortex core radius, resulting in the delay of tip vortex cavitation inception.

Lau, A., Berling, J., Koloschin, A., Holzaepfel, F., Linke, F. and Wicke, K.

"GROUND-BASED WAKE VORTEX PREDICTION IN THE EN-ROUTE EUROPEAN AIRSPACE"

AIAA Paper 2018-2879, June 2018, Atlanta, GA.

The present study deals with ground-based prediction of enroute wake turbulence encounters in the European airspace. Due to an increasing overall volume of air traffic with required navigation performance within highly congested enroute airspaces, wake turbulence encounters above flight level 100 are becoming more frequent during the last years. The prediction of enroute wake vortex encounters provides information about airspaces with an increased encounter probability as well as specific characteristics of potential encounters. Apart from safety-related benefits, this information may be applied during flight- and capacity planning processes. Two different types of models are coupled with each other: an air traffic flow management model and a wake vortex decay and transport model. The results provide information about the predicted number of en-route encounters, dominant spatial encounter configurations and their locations.

Lau, A., Lorenz, S. and Holzaepfel, F.

"INDIVIDUAL WAKE VORTEX SEPARATIONS: CAPACITY AND DELAY IMPACT ON SINGLE AND DUAL DEPENDENT RUNWAY SYSTEMS"

AIAA Paper 2012-5641, September 2012, Indianapolis, Indiana.

Airport capacity constraints and growing traffic demand in air transportation cause congestion and delay on the ground and in the air. Conservative wake turbulence separation minima in the approach phase guarantee a minimum of in-flight wake encounters of trailing aircraft. On the other hand, in

many situations weather-based separation minima could support more efficient runway utilization. This work estimates delay reduction and capacity gains of DLR's Wake Vortex Prediction and Monitoring System (WSVBS) through the application of reduced time-based approach separations for a single and dual dependent runway system. The system dynamically adjusts approach separations without compromising safety. Delay calculations are conducted with a dynamic runway queuing model, which is capable to process time varying approach separations. It provides the relevant delay data, where several representative operational scenarios enabled through the application of reduced separations on a single and dual dependent runway system are considered. Capacity profiles are created by processing WSVBS separation data with the actual traffic demand. The results give insight about possible delay reductions as well as related operational impact under given implementation assumptions. It is shown that the WSVBS provides efficiency gains on both runway systems, whereas operational requirements regarding the single runway system need to be considered applying reduced individual separations. Regarding the dual dependent runway system, an average hourly delay reduction up to 15 minutes maximum is revealed for the defined scenario setup.

Lauer, N., Yeo, D. W., Snyder, D. A. and Paley, D. A.

"TIP-VORTEX LOCALIZATION FOR CROSS-STREAM POSITION CONTROL OF A MULTI-HOLE PROBE
RELATIVE TO A STATIONARY WING IN A FREE-JET WIND TUNNEL"

AIAA Paper 2017-1484, January 2017, Grapevine, TX.

The continuing development of fully autonomous aircraft requires advanced sensing and control systems to complete difficult tasks such as aerial refueling and close formation flight. To accomplish such maneuvers, an aircraft must be able to measure the location of nearby aircraft and position itself relative to these other flight vehicles. In visually degraded environments where vision sensors might struggle, wake sensing provides an effective means of locating other aircraft. Using onboard velocity measurements, we combine a point-vortex model with a Bayesian filter to estimate a leader aircraft location through the sensing of wingtip wake vortices. We demonstrate the filtering strategy by estimating the position of a wing using experimental data in an open-jet wind tunnel. An experimental test-bed rapidly positions a flow measurement system within the wake of a wing in a free stream. A flow survey of the tip vortex within the aerodynamic wake of a leader aircraft, conducted with a multi-hole probe, measures velocities in the cross-stream plane. The wake position estimates are used for closed-loop control of the sensor position. This paper presents the estimation strategy and model, experimental data, closed-loop control simulation, and real-time wind tunnel feedback control results. In ongoing work, we are considering applications in which a follower aircraft senses the wake of a leader aircraft and positions itself for maximum aerodynamic efficiency.

Laukhin, I. A., Saltanov, G. A. and Savostianov, V. A.

"CALCULATION OF THE PARAMETERS OF NEAR-WAKE VORTICES"

Energetika, Vol. 22, June 1979, pp. 115-118

The analysis is carried out under the assumption that the near wake is a Karman street. The concept of a vorticity boundary layer is introduced. For given wake parameters and trailing edge thickness, a unique relationship between the boundary layer characteristics at the trailing edge and the vortex core and intensity is derived. The results of the analysis can be used to good advantage in the calculation of aerodynamic drags of bluff bodies, to-phase boundary layers, and aerodynamic noise.

Laursen, T. S., Rasmussen, J. J., Stenum, B. and Snezhkin, E. N.

"FORMATION OF A 2D VORTEX PAIR AND ITS 3D BREAKUP: AN EXPERIMENTAL STUDY"

Experiments in Fluids, Vol. 23, 1997, pp. 29-37.

Vortex pairs are studied using a dye tracing visualization technique and a particle tracking velocimetry system. The vortex pairs are produced by gravity induced inlets of water issued through a uniform gap. The inlet Reynolds number is $Re = Ud/\nu$ is approximately equal to 875 in all tests (d being the gap width and U the cross sectional mean velocity), i.e. the flow is in the laminar regime. Initially, the dipolar vortex structure is two-dimensional, but after travelling a distance of a few times its own width, the flow structure becomes unstable, breaks up and changes into a three-dimensional flow structure. The breakup appears to be caused by an axial flow in the core centers of each vortex of the dipolar structure. These axial flows are induced by boundary effects related to the von Karman viscous pump. After the breakup, it is believed that a vortex ring is formed through reconnection of rudiments from the dipolar structure mediated by the wall induced vorticity.

Lawrence, B. and Padfield, G. D.

"WAKE VORTEX ENCOUNTER SEVERITY FOR ROTORCRAFT IN APPROACH AND LANDING"

31st European Rotorcraft Forum, Florence, Italy, September 2005.

The Advisory Council for Aeronautics Research in Europe predicts that European air traffic may nearly triple by 2020. The growth in air traffic is already an increasing problem with capacity at some airports becoming limited due to congestion. This could be alleviated by providing additional passenger capacity at hubs through the introduction of rotorcraft using new IFR procedures and operating simultaneously but independently of the fixed-wing traffic. These Simultaneous Non-Interfering operations (SNIOPs) will be enabled by a 'reconfiguration' of the airspace, taking advantage of new navigational and air traffic management systems. SNIOPs raise critical safety questions for rotorcraft wake vortex encounters (WVE's) and will require consideration of the longitudinal and lateral aircraft separation and the locations of the rotorcraft FATO's (Final Approach and Take-Off areas). This paper presents analysis from work carried out as part of the Framework 6 project 'OPTIMAL' including the development of predictive methodology and analysis for rotorcraft WVE's using a severity rating scale. In particular, scenarios are considered where the rotorcraft is following precision glideslopes of up to 12 degrees in both good and degraded visual conditions. Handling qualities criteria have already been found to be well suited to investigating severity issues, by evaluating the pilot's perception of their ability to

overcome the effects of an encounter. Within this framework, draft boundaries are proposed for the acceptable severity of an encounter. Within this framework, draft boundaries are proposed for the acceptable severity of an encounter. Furthermore, a pilot may be able to recover from an encounter, but the question of whether the required navigational precision would be compromised and a go-around required is also addressed.

Lawrence, B. and Padfield, G. D.

"WAKE VORTEX ENCOUNTER SEVERITY FOR ROTORCRAFT IN FINAL APPROACH"

Aerospace Science and Technology, Vol. 12, 2008, pp. 385-397

The Advisory Council for Aeronautics Research in Europe predicts that European air traffic may nearly triple by 2020. The growth in air traffic is already an increasing problem with capacity at some airports becoming limited due to congestion. This could be alleviated by providing additional passenger capacity at hubs through the introduction of rotorcraft using new IFR procedures and operating simultaneously but independently of the fixed-wing traffic. These Simultaneous Non-Interfering operations (SNIOPs) will be enabled by a 'reconfiguration' of the airspace, taking advantage of new navigational and air traffic management systems. SNIOPs raise critical safety questions for rotorcraft wake vortex encounters (WVE's) and will require consideration of the longitudinal and lateral aircraft separation and the locations of the rotorcraft FATO's (Final Approach and Take-Off areas). This paper presents analysis from work carried out as part of the Framework 6 project 'OPTIMAL' including the development of predictive methodology and analysis for rotorcraft WVE's using a severity rating scale. In particular, scenarios are considered where the rotorcraft is following precision glideslopes of up to 12 degrees in both good and degraded visual conditions. Handling qualities criteria have already been found to be well suited to investigating severity issues, by evaluating the pilot's perception of their ability to overcome the effects of an encounter. Within this framework, draft boundaries are proposed for the acceptable severity of an encounter. Within this framework, draft boundaries are proposed for the acceptable severity of an encounter. Furthermore, a pilot may be able to recover from an encounter, but the question of whether the required navigational precision would be compromised and a go-around required is also addressed.

Lawrence, B., Padfield, G. D. and Taghizad, A.

"ROTORCRAFT WAKE VORTEX ENCOUNTERS: A FLIGHT MECHANICS PERSPECTIVE"

European Rotorcraft Forum, Maastricht, The Netherlands, September 2006.

The European Commission Framework VI project OPTIMAL is developing new rotorcraft and fixed-wing procedures to increase airport capacity, improve efficiency and reduce environmental impact. Among these procedures, the concept of rotorcraft Simultaneous Non-Interfering operations (SNIOPs) with heavy, runway-based fixed-wing traffic will feature. It has been identified that these operations present a potential risk for rotorcraft encountering the wake vortices of fixed-wing aircraft. The research presented is part of an ongoing effort to understand the flight mechanics of a rotorcraft Wake

Vortex Encounter (WVE) as well developing methods to assess the severity of a WVE. Models have been used in piloted simulation experiments and desktop simulations to include comparative studies of different rotorcraft configurations in a WVE. Parameters such as mass, rotor size, rotor speed and rotor stiffness have also been considered. This study also attempts to make the connection between a particular rotorcraft's sensitivity to a wake vortex and its basic design parameters through the use of flight stability and control derivatives. Results from piloted simulations will also be presented. The results build upon work presented at previous forums, incorporating new rotorcraft types and vortex encounter geometries. The paper presents results from the effort to create criteria for assessing severity and developing methods for linking the fast-time/offline simulation results to the piloted assessments. Establishment of such methods will allow the consideration of a greater number of configurations and scenarios, for example, in the development of safety cases for particular SNIOPs proposals.

Lawrence, R. S., Ochs, G. R. and Clifford, S. F.

"USE OF SCINTILLATIONS TO MEASURE AVERAGE WIND ACROSS A LIGHT BEAM"

Applied Optics, Vol. 11, No. 2, February 1972, pp. 239-243.

We report the successful construction and testing of an optical wind sensor that uses the motion of the scintillation pattern to measure the transverse component of wind blowing across a laser beam. As is done for measuring ionospheric and interplanetary winds, we use a correlation method. However, in our application, the slope at zero lag of the time-lagged correlogram proves to be more useful than the more commonly used delay to the peak. The reason is that, in the atmosphere, irregularities are distributed along the entire propagation path. We use a detector spacing of 0.33 of the diameter of the first Fresnel zone to obtain a nearly uniform weighting function along the path, though the center of the path is still more effective than the ends. The sensor has been used extensively over 1-km and 15-km paths, and field tests of various applications are planned.

Lawson, T. J. and Uk, S.

"THE INFLUENCE OF WIND TURBULENCE, CROP CHARACTERISTICS AND FLYING HEIGHT ON THE DISPERSAL OF AERIAL SPRAYS"

Atmospheric Environment, Vol. 13, Issue 5, 1979, pp. 711-71.

A series of aerial spray field trials using drops of size 10-230 microns were conducted to determine how the total amount of airborne spray varied with spray release height, drop size, downwind distance, turbulent airflow conditions and the nature of the underlying surface (wheat or fallow). By comparing the results with the predictions of a theoretical model of spray dispersal under turbulent conditions, it was possible to quantify both the removal efficiency of the underlying surface for various drop sizes, and the influence of the aircraft wing-tip vortices in changing the effective spray release height. The results are presented so that the total amount of airborne drift can be predicted from any atomizer, once the drop size spectrum produced by the atomizer is known. The variability due to turbulence of

the quantity of airborne spray between individual spray runs is assessed and implications drawn regarding the number of repeat trials necessary to show significant results.

Lay, J. E.

"AN EXPERIMENTAL AND ANALYTICAL STUDY OF VORTEX-FLOW TEMPERATURE SEPARATION BY SUPERPOSITION OF SPIRAL AND AXIAL FLOW, PART 2"

Journal of Heat Transfer, August 1959, pp. 213-222.

Part 2 reports on the analytical study. The free vortex motion of the gas upon entrance to the tube is mathematically superposed to a compressible sink to give a spiral flow in the plane. The characteristic existence of limit circles is corroborated by the experimental flow visualization. The solution in space is obtained by addition of a uniform axial velocity to the spiral flow. When viscosity effects are considered, the free vortex is shown to change into a forced vortex. The latter flow is one of minimum kinetic energy and maximum entropy. Energy considerations enable the determination of an optimum cold air radius to give largest stagnation temperature separation. Significantly, this was the radius that gave best performance in the experimental program.

Lay, J. E.

"AN EXPERIMENTAL AND ANALYTICAL STUDY OF VORTEX-FLOW TEMPERATURE SEPARATION BY SUPERPOSITION OF SPIRAL AND AXIAL FLOWS, PART 1"

Journal of Heat Transfer, August 1959, pp. 202-212.

This paper reports on an experimental and analytical study of compressible flow in a uniform vortex tube. Part 1 deals with an experimental study, Part 2 with the analytical study. Its purpose is to provide a better understanding of the separation of a gas stream into regions of high and low stagnation temperatures, there being at present little agreement as to the theory of operation. The problem is first approached from the experimental standpoint. A large, multipurpose vortex tube is so designed and built that pressure, temperature, and velocity traverses can be taken at six different stations throughout the length of the tube. Pressure, temperature, and velocity traverses are taken by means of hypodermic probes. Velocities are checked by means of a miniature hot-wire anemometer. Data are taken for different runs of inlet pressures and plotted against radial distance. Flow visualization is obtained by means of liquid injection. The analytical study consists of using superposition for the solution of the flow equations. It begins with potential vortex flow in the plane. The solution of this flow is characterized by the existence of sonic or limit circles. Superposition of a sink flow to the vortex solution yields a spiral flow in the plane. The general solution in space is obtained by addition of a uniform axial velocity to the spiral flow. When viscosity effects are considered, the potential vortex changes into a forced vortex, and the solution becomes a superposition of a viscous compressible sink to a forced vortex. Performance or stagnation temperature separation is expressed as function of the ratio of vortex strength to sink strength.

Lazorenko, V. and Dolhov, D.

"IMPLEMENTATION OF PLATE LINE SYSTEM IN UKRAINE"

Proceedings of the National Aviation University, Kyiv, Ukraine, 2014, pp. 71-75.

The article is devoted to the analysis of possible Plate Line implementation in Ukraine. Problems which might occur during the installation of given system in Boryspil International airport are defined. Advantages and disadvantages of Plate Line on the example of Boryspil International airport are considered.

Le Bouar, G., Costes, M., Leroy-Chesneau, A. and Devinant, P.

"NUMERICAL SIMULATIONS OF UNSTEADY AERODYNAMICS OF HELICOPTER ROTOR IN MANEUVERING FLIGHT CONDITIONS"

Aerospace Science and Technology, Vol. 8, 2004, pp. 11-25

This article presents a new time-marching fully unsteady method for simulating helicopter rotors in maneuvering flight conditions. The unsteady wake model is based on Mudry's theory which rigorously derives the evolution equation for the wake considered as a vortex sheet from the fluid dynamic equations. The numerical treatment of the sheet with a high-order panel representation allows an accurate simulation of the wake without using numerical regularization techniques. An unsteady lifting line model, based on Matched Asymptotic Expansion, is used to represent the blade and to extend the concept of induced velocities to unsteady configurations. A first application to the Bo 105 rotor in maneuvering flight shows that the method is capable to handle such kind of complex configuration.

Le Dizées, S., Brancher, P., Coustols, E., Nybelen, L. and Jacquin, L.

"PREVIOUS WORK AND PRESENT KNOWLEDGE ON VORTEX INSTABILITIES AND DECAY"

AST4-CT-2005-012238, CNRS-IRPHE, Toulouse, France, December 2005

The present review has been divided in five parts: Vortex meandering and wave propagation, End effects, Vortex bursting, Elliptic instability, and Long-wave cooperative instabilities. The review of present knowledge for the works planned in task 1.1.2 (End effects and bursting) has been split in three different parts. The fundamental aspects of end effects which concern the wave propagation phenomenon is reviewed together with vortex meandering (subtask 1.1.1) by P. Brancher and D. Fabre (IMFT). The end effects related with experiments are reviewed by E. Coustols (ONERA). The specific problem of vortex bursting is reviewed by L. Nybelen (CERFACS). The reviews for subtask 1.2.1 (elliptic instability) and subtask 1.2.2 (long-wave cooperative instabilities) are done by S. Le Dizés (IRPHE) and L. Jacquin (ONERA) respectively.

Le Dizes, S. and Fabre, D.

"LARGE-REYNOLDS-NUMBER ASYMPTOTIC ANALYSIS OF VISCOUS CENTRE MODES IN VORTICES"

J. Fluid Mech., Vol. 585, 2007, pp. 153-180

This paper presents a large-Reynolds-number asymptotic analysis of viscous center modes on an arbitrary axisymmetric vortex with an axial jet. By a multiple-scale matching analysis, we demonstrate the existence of three different families of viscous center modes. Our results prove that any vortex with a jet (or jet with swirl) is unstable if the Reynolds number is sufficiently large. The spatial structure of the viscous center modes is obtained and simple approximations which capture the main feature of the eigenmodes are also provided. The theoretical predictions are compared with numerical results for the q-vortex model (or Batchelor vortex) for Re greater than or equal to 100,000. For all modes, a good agreement is demonstrated for both the frequency and the spatial structure.

Le Dizes, S. and Fabre, D.

"LINEAR ASYMPTOTIC STABILITY ANALYSIS OF SPECIFIC VORTICES"

AST4-CT-2005-012238, CNRS-IRPHE, Toulouse, France, January 2006

This report presents a large-Reynolds-number asymptotic analysis of viscous centre modes on an arbitrary axisymmetrical vortex with axial jet. By a multiple-scale matching analysis, we demonstrate the existence of three different families of viscous centre modes. The spatial structure of the viscous centre modes is obtained and simple approximations which capture the main feature of the eigenmodes are also provided. The theoretical predictions are compared with numerical results for the Batchelor vortex (q-vortex model). For all modes, a very good agreement is demonstrated for both the frequency and the spatial structure.

le Dizes, S. and Lacaze, L.

"AN ASYMPTOTIC DESCRIPTION OF VORTEX KELVIN MODES"

Journal of Fluid Mechanics, Vol. 542, 2005, pp. 69-96.

A large-axial-wavenumber asymptotic analysis of inviscid normal modes in an axisymmetric vortex with a weak axial flow is performed in this work. Using a WKBJ approach, general conditions for the existence of regular neutral modes are obtained. Dispersion relations are derived for neutral modes confined in the vortex core or in a ring. Results are applied to a vortex with Gaussian vorticity and axial velocity profiles, and a good agreement with numerical results is observed for almost all values of k . The theory is also extended to deal with singular modes possessing a critical point singularity. We demonstrate that the characteristics for vanishing viscosity of viscous damped normal modes can also be obtained. Known viscous damped eigenfrequencies for the Gaussian vortex without axial flow, in particular, are shown to be predicted well by our estimates. The theory is also shown to provide explanations for a few of their peculiar properties.

Le Dizes, S. and Lacaze, L.

"LINEAR STABILITY ANALYSIS OF THE ELLIPTIC INSTABILITY IN VORTICES WITH AXIAL FLOW"

AST4-CT-2005-012238, Inst. de Recherche sur les Phenomenes Hors Equilibre, Marseille, France, October 2005

Vortices generated by aircraft wings are known to interact with each other. Each vortex, in particular, is subjected to the strain field induced by the other surrounding vortices. This strain field is at the origin of what is now called the elliptic instability which develops in vortex cores. For vortices without axial flow, this instability is characterized by a sinuous deformation of the vortices with a wavelength proportional to the vortex core size. The purpose of the present work is to demonstrate that other unstable modes are expected when there is an axial flow in the vortex core. The theory is developed for a Batchelor vortex in a stationary strain field. This model describes the situation in the far wake where the flow is composed of two counter-rotating Batchelor vortices. Similar qualitative conclusions are expected for other types of vortices, or vortices in rotating strain fields.

Le Dizes, S. and Laporte, F.

"THEORETICAL PREDICTIONS FOR THE ELLIPTICAL INSTABILITY IN A TWO-VORTEX FLOW"

J. Fluid Mech., Vol. 471, 2002, pp. 169-201

Two parallel Gaussian vortices of circulation C_1 and C_2 , radii a_1 and a_2 , separated by a distance b may become unstable by the elliptical instability due to the elliptic deformation of their cores. The goal of the paper is to analyze this occurrence theoretically in a general framework. An explicit formula for the temporal growth rate of the elliptical instability in each vortex is obtained as a function of the above global parameters of the system, the Reynolds number, and the non-dimensional axial wavenumber of the perturbation. This formula is based on a known asymptotic expression for the local instability growth rate at an elliptical stagnation point which depends on the local characteristics of the elliptical flow and the inclination angle of the local perturbation wavevector at this point. The elliptical flow characteristics are estimated by considering each Gaussian vortex alone in a weak uniform external strain field whose properties are provided by a point vortex modelling of the vortex pair. The inclination angle is obtained from the dispersion relation for the Gaussian vortex normal modes and the local expression near each vortex center for the two helical modes of azimuthal wavenumber $m = 1$ and $m = -1$ which constitute the elliptical instability global mode. Both the final formula and the hypotheses made for its derivation are tested and validated by direct numerical simulations and large-eddy simulations.

Le Dizes, S. and Verga, A.

"VISCOUS INTERACTIONS OF TWO CO-ROTATING VORTICES BEFORE MERGING"

J. Fluid Mech., Vol. 467, 2002, pp. 389-410

The viscous evolution of two co-rotating vortices is analyzed using direct two-dimensional numerical simulations of the Navier-Stokes equations. The article focuses on vortex interaction regimes before merging. Two parameters are varied: a steepness parameter, n , which measures the steepness of the initial vorticity profiles in a given family of profiles, and the Reynolds number, Re (between 500 and 16,000). Two distinct relaxation processes are identified. The first one is non-viscous and corresponds to a rapid adaptation of each vortex to the external (strain) field generated by the other vortex. This adaptation process, which is profile dependent, is described and explained using the damped Kelvin modes of each vortex. The second relaxation process is a slow diffusion phenomenon. It is like the relaxation of any non-Gaussian axisymmetric vortex towards the Gaussian. The quasi-stationary solution evolves on a viscous-time scale toward a single attractive solution which corresponds to the evolution from two initially Gaussian vortices. The attractive solution is analyzed in detail up to the merging threshold a/b nearly equal to 0.22 where a and b are the vortex radius and the separation distance respectively. The vortex core deformations are quantified and compared to those induced by a single vortex in a rotating strain field. A good agreement with the asymptotic predictions is demonstrated for the eccentricity of vortex core streamlines. A weak anomalous Reynolds number dependence of the solution is also identified. This dependence is attributed to the advection-diffusion of vorticity towards the hyperbolic points of the system and across the separatrix connecting these points.

Le Moigne, A. and Qin, N.

"LES WITH NUMERICAL DISSIPATION FOR AIRCRAFT WAKE VORTICES"

AIAA Paper No. 2006-1258, Reno, NV, January 2006

Large-Eddy Simulations of a pair of counter-rotating wake vortices in quiescent air are presented. The dissipation is entirely provided by the numerical schemes and grids since no sub-grid scale model is employed. Two numerical schemes are investigated for this purpose: an upwind scheme based on Osher's approximate Riemann solver and a MUSCL reconstruction, and a central difference scheme with fourth order artificial dissipation. The grids employed are unstructured, either entirely composed of tetrahedral cells or hybrid with a Cartesian structured core. The numerical results show that discretization scheme, grid refinement and grid topology have a strong influence on the amount of dissipation generated and hence on the accuracy of the simulations. The methodology can reproduce a realistic vortex decay with the appearance of short and long wave instabilities.

Le Roux, C.

"INCREASED AIRPORT CAPACITY THROUGH REDUCTION OF SEPARATIONS DUE TO WAKE VORTICES"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 4-1 - 4-6.

The reduction of separation standards due to wake vortices during approach and takeoff phases will allow, without any doubt, an increased airport capacity. The DGAC first goal is to define a system linked to the ATC allowing a wake vortex detection and alarm display in real time.

Le Roux, C. and Corjon, A.

"WAKE VORTEX ADVISORY SYSTEM IMPLEMENTATION AT ORLY AIRPORT FOR DEPARTING AIRCRAFT"

Air Traffic Control Quarterly, Vol. 5, No. 1, 1997, pp. 31-48.

The work done at Service Technique de la Navigation Aérienne (STNA) on wake vortices has led to the establishment of relationships between wind characteristics and potential hazards for a following aircraft. The methods that define these relationships and their validation are presented. Separation between aircraft is defined from our model as varying between 80 and 30 s for either a total wind of 12 to 20 kt or a crosswind of 5 to 8 kt. Based on these results, a first version of SYAGE (SYstème Anticipatif de Gestion des Espacements) has been defined which considers only a temporary change of the current separation matrix. This version of SYAGE will be applied only to take-off from a single runway because of the difficulty of forecasting wind characteristics, as would be required for a system applied also to landing. To optimize the system's efficiency, it is planned to link SYAGE 1 to a meteorological interface and to the Surface Movement and Guidance Control System (SMGCS) now under development. The objective is to realize a wake vortex advisory system (WVAS) for departing aircraft. Prior to implementing the WVAS at Orly Airport, a demonstration is planned to provide experience for controllers and pilots.

Le, T. H., Mege, P. and Morchoisne, Y.

"NUMERICAL SIMULATION OF VORTEX BREAKDOWN BY SOLVING THE EULER EQUATIONS FOR AN INCOMPRESSIBLE FLUID"

La Recherche Aérospatiale, No. 5, 1989, pp. 35-49.

A method of calculating unsteady, three-dimensional flows of inviscid incompressible fluid has been used in research on vortex breakdown. This method is based on the solution of the unsteady Euler equations in a velocity-pressure formulation, discretized by centered finite difference schemes, accurate to the second order. The application described is a single vortex that has an initial velocity profile resembling delta wing vortices. Comparisons are made with experimental data and with other simulation methods.

Le, T. H., Mege, P. H. and Morchoisne, Y.

"DETERMINATION DE CRITERES D'ECLATEMENT TOURBILLONNAIRE PAR RESOLUTION DES EQUATIONS D'EULER ET DE NAVIER STOKES"

Proceedings of Fluid Dynamic Panel Symposium, Vortex Flow Aerodynamics, AGARD, CP-494, Scheveningen, The Netherlands, October 1990, pp. 22-1 to 22-10.

The vortex breakdown plays a key role in aerodynamics, especially on fighter aircraft or missiles at high angles of attack. Despite many studies, the knowledge of vortex bursting phenomenon is not complete and no reliable criterion is available to characterize it. Based upon numerical simulations which solve the Euler or the Navier-Stokes equations, a parametric study is carried out on the configuration of an isolated vortex subjected to an initial perturbation. Results obtained from this study allow the specification of a criterion based upon an appropriately defined local Rossby number to determine the region where breakdown occurs.

Leblanc, S.

"ACOUSTIC EXCITATION OF VORTEX INSTABILITIES"

Physics of Fluids, Vol. 13, No. 11, November 2001, pp. 3496-3499

The asymptotic solution of Ford and Smith which describes the dynamics of a Kelvin vortex disturbed by a single large wavelength acoustic excitation, is shown to be unstable to three-dimensional short-wave nonlinear perturbations. This result might have interesting physical applications such as the destabilization of vortices in geophysics or engineering.

Leblanc, S., Le Duc, A. and Le Penven, L.

"ON THE STABILITY OF VORTICES IN AN IDEAL GAS"

Lectures in Physics, Vol. 555, 2000, pp. 205-220

Two distinct mechanisms of three-dimensional instability in compressible planar vortices in an ideal gas are presented. Both mechanisms have been obtained with the geometrical optics (WKB) stability theory which consists in studying the evolution of short-wavelength disturbances localized along the trajectories of the vortex. The first one corresponds to parametric resonances arising when a vortex is periodically compressed; the resulting instabilities are localized in the core of the vortex. On the contrary, in the second case, which corresponds to the generalization to compressible flows of the Rayleigh stability criterion for centrifugal instability, the growing perturbation surrounds the vortex at a given radius. In the latter case, the structure of the corresponding discrete eigenmodes may be described exactly, thus complementing and improving the WKB theory.

Leblebici, E. and Tuncer, I. H.

"OPENFOAM SOLUTIONS COUPLED WITH WRF FOR WIND POWER ESTIMATION"

AIAA Paper 2017-3062, June 2017, Denver, CO.

The open-source flow solver OpenFOAM is coupled with the mesoscale weather prediction software WRF in order to predict the atmospheric flows in complex terrains more accurately and to predict the daily energy production potential accurately. The low resolution, unsteady WRF solution provides the spatially varying unsteady boundary conditions for OpenFOAM solutions on high resolution terrain-fitted viscous grids. Coupled OpenFOAM solutions are successfully obtained for the Mersin/Mut region in Turkey. It is shown that the coupled solutions agree with the WRF solutions in general and compare well with the wind mast data available.

Leclaire, B., Sipp, D. and Jacquin, L.

"THE INFLUENCE OF UPSTREAM BOUNDARY CONDITIONS ON THE ONSET OF AXISYMMETRIC VORTEX BREAKDOWN IN A DUCT"

AIAA Paper No. 2008-3798, Seattle, WA, June 2008.

Past numerical studies on vortex breakdown in a duct have identified the choice of upstream boundary conditions as a source of major concern. While the choice for axial and azimuthal velocity profiles is often dictated by the experiments, the choice for the third upstream condition does not appear unanimous and its influence on the scenario of transition to breakdown is still unclear. Our purpose in this paper is to address this question in a theoretical framework. We investigate the axisymmetric flow of an inviscid fluid in a duct of constant cross-section and finite axial length. Solutions bifurcating from the columnar solution at criticality are analyzed via a weakly nonlinear expansion and computed in the fully nonlinear regime using numerical continuation, until a centerline recirculation is found at the duct outlet. The linear stability of these flows is also investigated. We apply these techniques to two typical flows frequently used in the literature: the Burgers-Rott vortex, and plug axial flow with solid body rotation.

Lecuona, A., Ruiz-Rivas, U. and Nogueira, J.

"SIMULATION OF PARTICLE TRAJECTORIES IN A VORTEX-INDUCED FLOW: APPLICATION TO SEED-DEPENDENT FLOW MEASUREMENT TECHNIQUES"

4th International Symposium on Particle Image Velocimetry, Paper 1116, September 2001, Gottingen, Germany.

The trajectories of heavy particles ($\rho_{\text{particle}}/\rho_{\text{fluid}}$ much greater than 1) are simulated in a 2D free vortex flow. The results show that heavy particles, even with small diameters, cannot properly trace the fluid and develop a centrifugal motion. This behavior leads to a quick depletion of particles in the vortex core, which, in seed-dependent measurements as PIV or LDV, produce a marked increase of measurement errors. Some examples are given and the evolution of the particle density is simulated.

Lee, B., Govindarajan, B. and Baeder, J. D.

"METHODS FOR EFFICIENT RESOLUTION OF VORTICAL STRUCTURES OF AN S-76 ROTOR IN HOVER"

AIAA Paper 2017-1664, January 2017, Grapevine, TX.

Meshing and numerical techniques are investigated to resolve the vortical structures of an S-76 rotor in hover in an efficient manner. The methodology employs a quarter domain Cartesian background mesh with periodic boundary conditions to reduce the computational costs in simulating all four blades of the rotor. Mesh clustering of the background grid is performed where the strong tip vortex is expected, and overset vortex tracking grids are added to further resolve the near-field evolution of the tip vortex. A compressible, structured, overset RANS based solver (OVERTURNS) is used in this study, and simulations were performed for a swept-tapered tip at a tip Mach number of 0.65 and a collective pitch angle of 9.25 degrees. To minimize the numerical error, a fifth-order Compact-Reconstruction Weighted Essentially Non-Oscillatory (CRWENO) is employed. A first-order temporal accurate scheme is applied to avoid excessive development of small eddies around the tip vortex and severe breakdown of far rotor wake. For turbulence closure, the Spalart-Allmaras one-equation model with the rotational correction terms (SA-R) and the Spalart-Allmaras Delayed Detached Eddy Simulation (SA-DDES) with modified parameters are tested. The performance parameters are examined, and the vortical structures are analyzed in detail, such as the tip vortex trajectory, swirl and axial velocity profiles, and Eddy viscosity. It was observed that while the vortex tracking grids, mesh clustering techniques, and use of SA-DDES do not significantly affect the predicted efficiency of the rotor, they vastly improve the quality of the wake structure trailed behind the rotor blades.

Lee, D. J. and Koo, S. O.

"NUMERICAL STUDY OF SOUND GENERATION DUE TO A SPINNING VORTEX PAIR"

AIAA Journal, Vol. 33, No. 1, January 1995, pp. 20-26.

A numerical approach for the calculation of an acoustic field is applied to the case of a spinning vortex pair to investigate the sound generation by quadrupole sources in unsteady vortical flows. Based on the unsteady hydrodynamic information from the known incompressible flowfield, the perturbed compressible acoustic terms derived from the Euler equations are calculated. Nonreflecting boundary conditions are developed to obtain highly stable solutions. Calculated results are compared with analytical solutions by the method of matched asymptotic expansions. The possibility of predicting the effect of convective mean flow is also tested. It is concluded that the sound generated by the quadrupole sources of unsteady vortical flows without a sound-generating body or surface can be calculated by using the source terms of hydrodynamic flow fluctuations.

Lee, D. J. and Na, S. L.

"NUMERICAL SIMULATIONS OF WAKE STRUCTURE GENERATED BY ROTATING BLADES USING A TIME MARCHING, FREE VORTEX BLOB METHOD"

European Journal of Mechanics - B/Fluids, Vol. 18, Issue 1, January-February 1999, pp. 147-159.

Velocity fields in the wake generated by rotating blades are calculated using a time-accurate, free vortex blob method without a non-physical model of the far wake. The computed free-wake geometry of a single rotor in hover is represented by three wake regions: a well-defined tip vortex region, an intermediate region, and an initially generated wake bundle. The simulated wake geometries in the radial and axial directions agree well with the experimental data for a two-bladed rotor for the overall regions of the wake. This agreement can be obtained by slowly increasing the rotational speed of the rotor blade, instead of using an impulsively rotating blade. The unsteady generation process of the wake structure is calculated for a single rotor with two blades.

Lee, D. J. and Smith, C. A.

"EFFECT OF VORTEX CORE DISTORTION ON BLADE-VORTEX INTERACTION"

AIAA Journal, Vol. 29, No. 9, September, 1991, pp. 1355-1362.

The effect of vortex distortion on the flow arising from the interaction of a convecting vortex and an airfoil is analyzed for two-dimensional, incompressible, inviscid flow. Significant distortion of the vortex structure, owing to interaction with the airfoil, can occur, especially during close interactions. The vorticity field is represented by multiple vortex elements. Vortex instability and diffusion, resulting from discretization in space and time, are discussed. An integral-boundary-element method is used to represent the airfoil surface and its effect on the flowfield. The body panels are redistributed on the surface as the vortices are convected past the airfoil to calculate the effect of the vorticity field more accurately. The method is applied to several cases to examine effects of vortex strength, distribution, and initial separation position. The distortion, even splitting, of the vortex core is observed for the case of close interaction. However, the extent of distortion depends strongly on the initial size and strength of the vortex. Also, the unsteady pressure term contributes significantly to both the surface-pressure distribution and total lift in addition to the quasi-steady term. Circulation around the airfoil is also presented.

Lee, G. H.

"TRAILING VORTEX WAKES"

Aeronautical Journal, September 1975, pp. 377-388.

It is shown that the trailing vortex wakes generated by large airplanes can cause serious upsets (loss of control) to smaller following aircraft that may encounter them and may damage buildings near an airport. The increase in separation behind big aircraft imposed as a safety measure leads to a serious loss of runway capacity. After discussion of the nature of wake vortices, it is demonstrated that they may be attenuated, so avoiding unnecessary separation between aircraft at an airport and, at the same time, obviating ground damage. Discussion of alternative devices available for moderating the vortex wake indicates that practical solutions may be confidently expected.

Lee, H. and Schetz, J. A.

"COMPUTATIONAL AND EXPERIMENTAL STUDY OF TRAILING VORTICES"

AIAA Paper No. 1983-1868, Danvers, MA, July 1983

A coordinated computational and experimental study was undertaken to investigate the behavior of the vortices trailing from low aspect ratio lifting surfaces. Vortex formation in the near-wake was measured in a wind tunnel with yaw-head and hot-wire probes at three different Reynolds numbers, the highest of which was greater than most previous studies. These near-wake measurements provided initial conditions for the far-field computation with the parabolized Navier-Stokes equations written in terms of the vorticity and a stream function. Turbulent transport was modeled through the turbulent kinetic energy and the Prandtl-Kolmogorov hypothesis to give an eddy viscosity. The experimental results showed that the effects of Reynolds number are significant for vortex formation in the near-wake, and the computation adequately predicted these effects. However, the decay trend in the far-field is essentially unaffected by the Reynolds number. The predicted decay for maximum tangential velocity agreed very well with Iversen's data correlation.

Lee, H. and Schetz, J. A.

"EXPERIMENTAL RESULTS FOR REYNOLDS NUMBER EFFECTS ON TRAILING VORTICES"

Journal of Aircraft, Vol. 22, No. 2, February 1985, pp. 158-160

The simulation of vortices by small-scale model testing in wind tunnels and towing tanks presents a problem, since the history of vortices is known to be sensitive to Reynolds number. The near-wake behavior of the vortices trailing from low aspect ratio lifting surfaces mounted on either side of a larger, non-lifting, streamlined strut was investigated in a wind tunnel. The effect of Reynolds number was apparent; an increasing Reynolds number corresponded to a decreasing axial velocity defect and an increasing maximum swirl velocity. Furthermore, this Reynolds number effect was found to be greater than that of downstream distance.

Lee, H.-T. and Chatterji, G. B.

"CLOSED-FORM TAKEOFF WEIGHT ESTIMATION MODEL FOR AIR TRANSPORTATION SIMULATION"

AIAA Paper No. 2010-9156, September 2010, Fort Worth, TX.

Takeoff weight is an important parameter for computing accurate aircraft trajectories. Most systems used for simulating air traffic and for providing air traffic management decision support use takeoff weights that depend only on the aircraft type. This paper proposes a closed-form algorithm for estimating takeoff weights based on flight plan and aircraft performance data. The algorithm is derived by combining the constant-altitude-cruise range equation with the weight estimation procedure commonly used in aircraft design. The model first determines whether the payload is limited by payload capacity, maximum takeoff weight, or fuel tank capacity, and then calculates the takeoff weight accordingly. The model is verified against manufacturer provided payload range diagrams for a jet and a

turboprop aircraft. Accurate and fast takeoff weight estimation with negligible computational overhead will enhance large scale air traffic simulations by improving the accuracy of trajectories and fuel burn estimates. Improvement in trajectory and fuel burn estimates will benefit the assessment of noise and emissions as well as improve the accuracy of automated conflict detection and resolution algorithms.

Lee, J.

"AERODYNAMIC CHARACTERISTICS OF RECTANGULAR WING WITH SQUARE LATERAL TIP"

AIAA Paper 2013-0250, January 2013, Grapevine, TX.

A numerical study has been conducted to investigate aerodynamic characteristics and the behavior of wing-tip vortices of the three-dimensional symmetric wing (NACA0015) in the vicinity of the ground. Two distinct phenomena, ground effect and Venturi effect, can be observed when the wing is approaching the ground and change the aerodynamic characteristics significantly. The symmetric wing in the vicinity of the ground shows both phenomena according to the pitch angles. The ground effect increases the lift and decreases the drag, simultaneously, but the Venturi effect decreases the lift and decreases the drag, significantly. The high dynamic pressure, and positive wing tip vortex of the Venturi effect augment the friction drag and the induced drag dramatically, unlike the ground effect. The vortex core at the wing tip moves into the center of the wing when the Venturi effect is dominant whereas the vortex core moves outward when the ground effect is dominant.

Lee, J. H., Sevil, H. E., Dogan, A. and Hullender, D.

"ESTIMATION OF RECEIVER AIRCRAFT STATES AND WIND VECTORS IN AERIAL REFUELING"

Journal of Guidance, Control and Dynamics, Vol. 37, No. 1, January-February 2014, pp. 265-276.

A square root unscented Kalman filter is used to estimate the states of a receiver aircraft and the components of the wind the aircraft is exposed to as it flies behind the tanker aircraft. The wind is the superposition of time-varying prevailing wind, turbulence, and the tanker's wake-induced wind. The system update of the estimator uses the nonlinear aircraft model, augmented by a nonlinear wind model, obtained from the translational dynamics of the aircraft. The aircraft state estimates are successfully used in controlling the position of the receiver aircraft relative to the tanker flying straight level and making turns. Although the performance of the estimation and control is very dependent on the covariance and correlation time constants of the sensor measurement errors, the estimated state feedback performs better than measured state feedback with higher levels of measurement noise and turbulence intensity.

Lee, J., Birch, S. F. and Scovill, B. A.

"AIRPORT JET PLUME ZONE MAPPING"

Journal of Aircraft, Vol. 33, No. 4, July-August 1996, pp. 737-742.

A software package, which maps the jet plume zones for a jet aircraft during airport ground operation, has been developed. The method generates an airport plume zone map by predicting plume velocity contours (for a selected jet plume velocity level, e.g., 35 mph) as a function of the aircraft geometry and engine power setting. The velocity contours are then superimposed on a pre-digitized airport map. A standard normalized velocity contour plot, which is unique to each airplane configuration, is used to quickly determine the plume velocity contour for an engine power setting and a computer graphics program is used to display an airport plume zone map on the computer screen. The method is general and is applicable to any airplane configuration. The purpose of this article is to introduce an airport plume zone mapping tool to the airplane design and operation groups.

Lee, J., Han, C. and Bae, C.-H.

"INFLUENCE OF WING CONFIGURATIONS ON AERODYNAMIC CHARACTERISTICS OF WINGS IN GROUND EFFECT"

Journal of Aircraft, Vol. 47, No. 3, May-June 2010, pp. 1030-1040.

A numerical analysis is performed to investigate the aerodynamic characteristics and the static height stability of the endplate and the anhedral angle on an aspect-ratio-one wing-in-ground effect. The analysis shows that the ground effect increases the lift by the high pressure on the lower surface, reduces the drag, increases the suction on the upper surface, and considerably enhances the lift-drag ratio. The endplate, which prevents the high-pressure air from escaping out of the lower surface and reduces the influence of the wing-tip vortex, further augments the lift and the lift-drag ratio. Irodov's criteria are also numerically evaluated to investigate the static height stability. The comparison of Irodov's criteria shows that the endplate is not favorable for the static height stability. However, the anhedral angle improves the lift as well as Irodov's criteria at various angles of attack and heights. Interestingly, the stagnation point for the anhedral angle moves forward with decreasing height at the low angles of attack and leads an increase in the pressure drag. Thus, the lift-drag ratio of a wing is not improved as much with an anhedral angle as it is with an endplate.

Lee, J., Xiao, Z., Burggraf, O. R., Conlisk, A. T. and Komerath, N. M.

"AN INVISCID ANALYSIS OF VORTEX-SURFACE COLLISIONS"

AIAA Paper 1995-2237, June 1995, San Diego, CA.

This work is part of a project designed to better understand the unsteady effects resulting from the close interaction of a rotor-wake tip-vortex with an airframe. The objective is to predict the unsteady air-loads associated with the rotor tip-vortex interaction with a helicopter airframe. In this paper we describe the results of a model developed to illustrate an inviscid mechanism for redistribution of vorticity concentrated initially in the vortex core as the vortex collides with a surface. Experiments

indicate that a strong suction peak generated as the tip-vortex approaches the airframe is rapidly reduced and the pressure soon returns to a locally quasi-steady distribution having a near-zero mean. The present model exhibits the same trends; in particular, it is shown that the vortex core bulges and the vorticity decays when the axial velocity in the core of the vortex is toward the surface. This is precisely what is seen in experiments on the advancing rotor side of the helicopter airframe.

Lee, L. and Lee, T.

"OSCILLATING-WING TIP VORTEX WITH PASSIVE SHORT-SPAN TRAILING-EDGE FLAPS"

Journal of Aircraft, Vol. 43, No. 3, May-June 2006, pp.723-731

Tip vortex flow behind an oscillating NACA 0015 wing with passive short-span trailing-edge flaps was investigated experimentally at $Re = 1.81 \times 100,000$. The spoiler was found to be very effective in diffusing the tip vortex, in terms of the reduction of peak tangential velocity and vortex strength, compared to a baseline wing; it also led to additional vertical upward displacement of the vortex center. No significant influence on the vortex size was observed, however. The spoiler-induced negative camber effects also translated into slightly reduced bound circulation, total lift, and lift-induced drag. For a tab, the dynamic increase-decrease in the vortex size and strength persisted and had values larger than for a baseline wing. No substantial change in the peak tangential velocity, compared to that for a baseline wing, was noticed. The axial core velocity was always wakelike, and the vortex center was shifted relatively outboard and vertically downward below the baseline wing. The tab also led to an increase in the lift and drag forces. The symmetric flap provided a compromise in the critical vortex-flow quantities between the spoiler and tab cases.

Lee, L. and Lee, T.

"EFFECT OF GURNEY FLAP ON UNSTEADY WAKE VORTEX"

J. Aircraft, Vol. 44, No. 4, July-August 2007, pp. 1398-1401

The influence of a Gurney flap, in both regular and inverted arrangements, on the critical vortex flow parameters of an oscillating NACA 0015 wing was investigated. The larger the Gurney flap height, the higher the core radius and circulation but the lower the peak tangential velocity. The core vorticity and axial velocity were significantly reduced by the presence of Gurney flaps. For an oscillating wing equipped with an inverted Gurney flap, the reduction in peak tangential velocity and core circulation was found to be most overwhelming and was accompanied by a considerable reduction in peak vorticity and mean axial core velocity throughout the entire oscillation cycle. The larger the inverted flap height, the smaller the peak tangential velocity, peak vorticity, and mean axial core velocity and the narrower the associated hysteresis.

Lee, S. and Bershader, D.

"HEAD-ON PARALLEL BLADE-VORTEX INTERACTION"

AIAA Journal, Vol. 32, No. 1, January 1994, pp. 16-22.

An experimental and computational study was carried out to investigate the parallel head-on blade-vortex interaction (BVI) and its noise generation mechanism. A shock tube, with an enlarged test section, was used to generate a compressible starting vortex which interacted with a target airfoil. The dual-pulsed holographic interferometry (DPHI) technique and airfoil surface pressure measurements were employed to obtain quantitative flowfield data during the BVI. A thin-layer Navier-Stokes code (BV12D), with a high-order upwind-biased scheme and a multizonal grid, was also used to simulate numerically the phenomena occurring in the head-on BVI. The detailed structure of a convecting vortex was studied through independent measurements of density and pressure distributions across the vortex center. Results indicate that, in a strong head-on BVI, the opposite pressure peaks are generated on both sides of the leading edge as the vortex approaches. Then, as soon as the vortex passes by the leading edge, the high-pressure peak suddenly moves toward the low-pressure peak - reducing in magnitude as it moves - simultaneously giving rise to the initial sound wave. In both experiment and computation, it is shown that the viscous effect plays a significant role in head-on BVIs.

Lee, S. and Bershader, D.

"THE STRUCTURE OF COMPRESSIBLE STARTING VORTICES"

Experiments in Fluids, Vol. 16, 1994, pp. 248-254.

The structures of highly two-dimensional shock-induced compressible starting vortices were investigated. Density distributions across the vortex were measured by dual-pulsed holographic interferometry. Pressure profiles of the vortex were measured by fast-response miniature Kulite transducers. From these two independent measurements the velocity profile was calculated using the radial momentum equation. The detailed vortex structure is like that from the tip of a wing and consists of four well-defined regions: a core region, a logarithmic region, a transition region, and an inviscid region. The distribution of circulation of the vortices can be expressed by a set of empirical formulae. The proportionality constants of the logarithmic region were found to be 0.43 ± 0.01 for three different two-dimensional vortices.

Lee, S. and Lee, J.

"AERODYNAMIC CHARACTERISTICS OF A RECTANGULAR WING IN GROUND PROXIMITY"

Journal of Aircraft, Vol. 51, No. 2, March-April 2014, pp. 688-692.

Depending on the heights and the angles of attack, the aerodynamic characteristics and the behavior of the wing-tip vortex are significantly changed. The flow characteristics can be clearly explained by the Venturi effect and the ground effect. When the angle of attack is less than 4 deg, the gap between the pressure side and the ground clearly shows the Venturi effect due to the convergence-divergence passage. When the Venturi effect is dominant, negative lift and the drag due to friction, flow separation, and induced vortex dramatically increase simultaneously. The wing-tip vortex sucked into the pressure side moves close to the center of the wing. The induced drag is increased as well as the

friction drag due to the high dynamic pressure on the pressure side. This high dynamic pressure increases the suction on the lower surface. Therefore, the negative vortices are generated and move in the negative spanwise direction. In contrast, when the ground effect (angle of attack greater than 4) is dominant, the lift is augmented, but the drag decreases as the height decreases. The induced drag and friction drag are diminished, and the aerodynamic characteristics improve as height decreases. The negative vortex is generated at the wing tip and drifts outward. At the intermediate angle of attack (4 deg), both effects are present simultaneously, and so the lift and the drag are not changed significantly as height changes. In this study, using a symmetric airfoil, we can show significant lift changes due to the Venturi effect and the ground effect, depending on the angle of attack. Despite the presence of a cambered or optimized airfoil, there is a severe lift decrease under the critical angle of attack. Thus, the critical angle of attack is critical for the safety and the efficiency of a vehicle operating in the ground effect.

Lee, S.-J., Shin, J.-W., Arndt, R. E. A. and Suh, J.-C.

"ATTENUATION OF THE TIP VORTEX FLOW USING A FLEXIBLE THREAD"

Experiments in Fluids, Vol. 59, 2018, pp. 23-2 to 23-12.

Tip vortex cavitation (TVC) is important in several practical engineering applications. The onset of TVC is a critical concern for navy surface ships and submarines that aim to increase capability to evade detection. A flexible thread attachment at blade tips was recently suggested as a new method to delay the onset of TVC. Although the occurrence of TVC can be reduced using a flexible thread, no scientific investigation focusing on its mechanisms has been undertaken. Thus, herein, we experimentally investigated the use of the flexible thread to suppress TVC from an elliptical wing. These investigations were performed in a cavitation tunnel and involved an observation of TVC using high-speed cameras, motion tracking of the thread using image-processing techniques, and near-field flow measurements performed using stereoscopic particle image velocimetry. The experimental data suggested that the flexible thread affects the axial velocity field more than the circumferential velocity field around the TVC axis. Furthermore, we observed no clear dependence of the vortex core size, circulation, and flow unsteadiness on TVC suppression. However, the presence of the thread at the wing tip led to a notable reduction in the streamwise velocity field, thereby alleviating TVC.

Lee, S.-Y.

"THE VORTEX AERODYNAMICS OF DELTA WINGS"

AIAA Paper 2016-4171, June 2016, Washington, DC.

Based on a proposed vortex/circulation model, this paper presents a set of equations representing the aerodynamic forces on a delta wing. In addition to the potential lift due to the bound circulation on the wing, a novel expression for the force due to the leading-edge separation vortex is established and is identified as the 'Linear Crossflow Vortex Force.' An empirical formula is also employed for the non-linear drag component. Since experimental data indicate that, at small to intermediate aspect ratios,

there is no contribution from the drag free pure potential lift and it can, thereby, be omitted. As a result, the sum of linear and non-linear normal forces from the current theory matches the experiments accurately, indicating that the aerodynamics is dominated by the crossflow vortex force. A function emulating the vortex breakdown behavior extend the data fit to post stall conditions. For larger aspect ratios, a much higher lift arises while the predicted vortex normal force begins to diminish, resulting in a transition to potential lift dominance. The current solution supports such a transition and converges to the classical infinite wing at very large aspect ratio. An examination of the right-angle apex planform, with aspect ratio of 4, demonstrates the shifting contribution from all lift components as the angle of attack increases, attributable to both leading edge separation and vortex breakdown phenomena.

Lee, S.-Y.

"THE VORTEX IMPULSE THEORY OF WING AERODYNAMICS"

AIAA Paper No. 2004-4733, Providence, RI, August 2004

A kinematic model of flow on an infinite flat plate is established, describing how the circulatory flow field is developed on the plate and how the circulation slips off to form wake vortices. The two-dimensional model is then extended to rectangular plates, proposing a circulation distribution relationship over the span that describes its dependency on the finite plate geometry. Built on these observations, a quasi-steady vortex impulse analysis method is developed and applied to calculate the linear, potential lift and drag forces on the plate. The results match remarkably well with experimental data. Several key findings are reported in the study: 1) the no-flow condition on the solid surface boundary is determined to be the sole cause for circulatory flows. More precisely, the circulation caused by the reactive flow at centerline yields the exact Kutta-Joukowski circulation expression. Shedding of the leeward circulation leaves the windward half attached to the wing, producing aerodynamic lift. 2) for wings of finite span, due to the presence of side edges, the circulatory flow must emanate in radial directions. As a result, the lifting capability is reduced due to this 'circulation diffusion effect'. The analytical expressions derived yield very accurate results compared to experiments but differ substantially in representation from the classical Prandtl 'Lifting-line Theory'.

Lee, T.

"EFFECTIVENESS OF DYNAMICALLY DEFLECTED TAB CONTROL OF A TIP VORTEX"

AIAA Journal, Vol. 45, December 2007, pp. 2994-3002

The control of the tip vortex generated by an oscillating NACA 0015 wing via a dynamically deflected trailing-edge tab, actuated at 29 different start times, amplitudes, and ramp-up rates, was investigated. The upward tab deflection was found to be more effective in weakening the peak tangential velocity and vortex strength than the downward deflection, regardless of the start time and ramp-up rate. A pair of corotating vortices was persistently noticed during pitch-up. An earlier and faster tab deflection (actuated during pitch-up) led to a larger reduction in the core vortex flow quantities. The downward

tab deflection was, however, more effective in displacing the vortex position and in diffusing the vortex. The later and slower the downward tab actuation, the larger the vortex displacement and diffusion that took place. The largest reduction in the vortex strength was obtained with a start time at the beginning of pitch-down. The effectiveness of the tab control was also evaluated via the hysteretic behavior of the vortex core flow quantity and the potential suppression of the blade-vortex-interaction noise.

Lee, T.

"PIV STUDY OF NEAR-FIELD TIP VORTEX BEHIND PERFORATED GURNEY FLAPS"

Experimental Fluids, Vol. 10, 2010.

The impact of Gurney flaps, of different heights and perforations, on the growth and development of a tip vortex, both along the tip and in the near field of a finite NACA 0012 wing, at $Re = 105000$ was investigated by using particle image velocimetry (PIV). Wind-tunnel force balance measurements were also made to supplement the PIV results. This study is a continuation of the work of Lee and Ko on the near-wake measurements behind perforated Gurney flaps. The present results show that along the tip, the overall behavior of the secondary vortices and their interaction with the primary, or tip, vortex remained basically unchanged, regardless of flap height and always exhibited a local maximum at $x/c = 0.8$ (from the leading edge). In the near field, the strength and structure of the near-field tip vortex were found to vary greatly with the flap height and perforation. The small flaps produced a more concentrated tip vortex with an increased circulation, while the large Gurney flaps caused a disruption of the tip vortex. The disrupted vortex can, however, be re-established by the addition of flap perforation. The larger the flap perforation the more organized the tip vortex. The Gurney flaps have the potential to serve as an alternative off-design wake vortex control device.

Lee, T. and Aboelkassem, Y.

"INTERACTION OF A STREAMWISE VORTEX WITH A BLADE TIP VORTEX"

Journal of Aircraft, Vol. 43, No. 6, November-December 2006, pp. 1956-1958

The downstream development of a streamwise vortex interacted with a blade tip vortex was investigated. For separation distances $= 0$, the peak tangential velocity of the interaction vortex remained basically unchanged, whereas core circulation and core radius were increased approximately linearly with x/c . For separation distance < 0 , the generator vortex interacted constructively with the blade tip vortex of the same sign to create a single and stronger interaction vortex (i.e., a constructive mode). The values of core radius, core circulation and tangential velocity of the interaction vortex increased with reducing the absolute value of the separation distance and exhibited a local maximum at separation distance $= 0$. For separation distance > 0 , the passing generator vortex paired with the blade vortex of the same sign to create a field of a vortex pair (i.e., a pairing mode) with the generator vortex of larger core radius and core circulation but lower tangential velocity than the blade vortex.

Lee, T. and Lan, C. E.

"NAVIER-STOKES CALCULATION OF WING WAKE STRUCTURE"

AIAA Paper 1994-1882, June 1994, Colorado Springs, CO.

A 'flow embedding' method in Navier-Stokes calculation is developed to calculate a detailed wing wake structure. The method allows the calculation to be completed in two stages, first a global solution with a coarse grid and then the embedded solution in a small region of interest with a dense grid. The boundary condition for the latter is provided by the former. This embedded flow method is shown to produce a detailed and accurate wake structure for a 76-degree-delta wing by comparing the results with available data in the near wake. The computed results for the delta wing further downstream indicate that there are two concentrated vortices, one being the leading-edge vortex, and the other being the trailing vortex, rotating opposite to each other. These two vortices stay strong and well organized from feeding of wake shear layers. The total pressure and axial velocity of both vortices are increasing in the downstream direction. The leading-edge vortex tends to move down and outboard in the downstream direction; while the trailing vortex stays above the leading-edge vortex and moves inboard. For a rectangular wing of aspect ratio 6, the calculated results are also compared with the near-wake data. Again, two vortices are identified, one being the conventional tip vortex and the other being the trailing vortex. The tip vortex is formed at the wing tip and moves outboard and upward; while the trailing vortex is formed downstream of the trailing edge from the roll-up of shear layer and tends to move inboard and downward. The calculated results for the rectangular wing also indicate that the vorticity associated with the trailing vortex becomes more concentrated even though its magnitude decreases downstream. Calculated total velocity in the core and the maximum tangential velocity around the trailing vortex core are shown to agree reasonably well with experimental data.

Lee, T. and Nikolic, V.

"EFFECTS OF A MOVABLE TIP STRAKE ON WAKE VORTEX STRUCTURE"

Journal of Aircraft, Vol. 45, No. 4, July-August 2008, pp. 1305-1314.

The impact of a tip-mounted strake, set at different deflection angles relative to the main-wing chord plane on the near-field wake vortex structure, and the associated lift-induced drag were investigated experimentally at $Re=191,000$. Force-balance aerodynamic forces were also obtained to supplement the wake vortex measurements. The results show that in addition to its substantial influence on the aerodynamic performance, the presence of the strake also led to an earlier completion of the rolling up of the tip vortex, compared with the baseline wing. The tip vortex had a reduced peak tangential velocity and core axial velocity but an increased core radius, compared with the baseline wing. These vortex core flow quantities increased with increasing strake angle. The core and total circulation increased above and remained below the baseline-wing value for a strake angle greater than 5 deg and less than 5 deg, respectively. The lift-induced drag, computed by using the Maskell induced-drag model,

was found to increase nonlinearly with strake angle and became larger than the baseline wing for a strake angle greater than 5 deg.

Lee, T. and Pereira, J.

"PASSIVE CONTROL OF UNSTEADY-WING TIP VORTEX VIA A SLENDER HALF-DELTA WING IN BOTH REVERSE AND REGULAR CONFIGURATIONS"

Experimental Fluids, Vol. 55, 2013, pp. 1564-1 to 1564-10.

The passive control of the tip vortex generated by an oscillating NACA 0012 wing via a tip-mounted half-delta wing, in both regular and reverse configurations, was investigated experimentally at $Re = 245,000$. Velocity and vorticity measurements, performed using a miniature triple hot-wire probe, show that vortex breakdown occurred when the half-delta wing (HDW) was mounted, but not for the reverse half-delta wing (RHDW) configuration. The HDW vortex breakdown led to a rapidly diffused tip vortex, suggesting an enhanced wake-vortex decay. For the RHDW wing configuration, the tip vortex remained concentrated but had a smaller size and also a weaker strength and rotation compared to the oscillating baseline wing. In addition, the vortex center of the oscillating RHDW wing-generated tip vortex was also found to be greatly displaced, especially in the transverse direction, which could translate into an increased blade-vortex-impingement miss distance and, as a result, an alleviated blade-vortex interaction.

Lee, T. and Pereira, J.

"IMPACT OF SHORT-SPAN STRIP ON OSCILLATING-WING TIP VORTEX"

Experiments in Fluids, Vol. 43, 2007, pp. 617-626

The impact of 12 spoiler-tab configurations, of different heights and widths, on the tip vortex generated by an oscillating NACA 0015 wing was investigated experimentally. For an oscillating wing equipped with a spoiler, the peak tangential velocity and core and total circulation were greatly reduced compared to a tab, regardless of its width, while the core radius remained largely unaffected with its center displaced vertically above the baseline wing. The most noticeable impact of a spoiler with a reduced height was its potential in alleviating the blade vortex interaction (BVI) strength. Meanwhile, the largest favorable impact on the critical vortex flow parameters was achieved via a 25%-span spoiler-tab combination with a height of 5 and 2.5% chord, respectively. A contrary effect on the BVI suppression, especially during pitch-up, was, however, observed. The impact on the BVI can be improved by reducing the height of the spoiler at the expense of unfavorable change in the vortex strength and displacement.

Lee, T. and Pereira, J.

"NATURE OF WAKELIKE AND JETLIKE AXIAL TIP VORTEX FLOWS"

Journal of Aircraft, Vol. 47, No. 6, Nov.-Dec. 2010, pp. 1946-1954.

The mechanisms responsible for the wake like and jet like axial flows of a tip vortex were investigated experimentally at $Re = 307000$. Both square and round tips were tested. Along the wing tip, a pocket of a higher-than-freestream, or jet like, fluid was continually present, regardless of the tip condition and airfoil angle of attack. Its maximum velocity increased with angle of attack and always exhibited a peak value around the trailing edge. In the near field, this jet like fluid pocket was entrained by the shear layers and the wing wake, and it resulted in a wake like axial flow for smaller angles of attack. For higher angles of attack, the jet like fluid pocket was, however, surrounded by the shear layers that, in turn, protected it from the destructive effects of the wing wake and remained jet like. The switchover angle at which the axial flow switched from wake like to jet like appeared around 7 degrees regardless of the tip condition, which also coincided with the angle at which the lift-to-drag ratio was a maximum. Finally, the round-tip-produced vortex was more concentrated and had a higher peak tangential velocity and core circulation but a smaller core radius compared with those of the square tip.

Lee, T. and Su, Y. Y.

"WINGTIP VORTEX CONTROL VIA THE USE OF A REVERSE HALF-DELTA WING"

Experimental Fluids, Vol. 52, 2012, pp. 1593-1609.

The effect of a 65-degree-sweep reverse half-delta wing (RHDW), mounted at the squared tip of a rectangular NACA 0012 wing, on the tip vortex was investigated experimentally at $Re = 245,000$. The RHDW was found to produce a weaker tip vortex with a lower vorticity level and, more importantly, a reduced lift-induced drag compared to the baseline wing. In addition to the lift increment, the RHDW also produced a large separated wake flow and subsequently an increased profile drag. The reduction in lift-induced drag, however, outperformed the increase in profile drag and resulted in a virtually unchanged total drag in comparison with the baseline wing. Physical mechanisms responsible for the RHDW-induced appealing aerodynamics and vortex flow modifications were discussed.

Lee, T. E., Leishman, J. G. and Ramasamy, M.

"FLUID DYNAMICS OF INTERACTING BLADE TIP VORTICES WITH A GROUND PLANE"

Journal of the American Helicopter Society, Vol. 55, 2010, pp. 022005-1 to 022005-16.

Flow visualization and phase-resolved particle image velocimetry (PIV) experiments were conducted on a hovering rotor to help understand the fluid dynamics of its vortical wake as it interacted with a horizontal ground plane. Visualization was performed by illuminating submicron tracer particles using a strobed laser sheet that was phase locked to the rotational frequency of the rotor. Two-component PIV measurements of the flow in radial planes were obtained at four rotor heights off the ground. Measurements at several wake ages were obtained to examine the morphology of the wake-surface interaction process. The results showed that the rotor wake and its downwash flow are initially subjected to powerful curvature and straining effects as it is deflected into a radially outward direction at the ground plane. An unsteady outward flow comprising a wall jet then developed in the region

between the ground plane and the vortical remnants of the rotor wake. The viscous processes of diffusion, vorticity intensification by straining, as well as turbulence generation were all shown to be factors affecting the fluid dynamics of the resulting flow field. In general, the tip vortices were found to induce significantly unsteady flow velocities if they reached the ground plane without undergoing substantial diffusion, especially when they remained coherent enough for adjacent vortices to pair and possibly merge. Further away from the rotor, the turbulence and velocity gradients in the developing wall jet were noted to shear the tip vortices and accelerate the diffusion of vorticity. An intermediate rotor height off the ground was found where the diffusion of vorticity was countered by the straining effects in the flow, which in this case resulted in the highest flow velocities and shear stresses on the ground plane.

Lee, T., Birch, D. and Gerontakos, P.

"VORTEX SHEDDING AND SPACING OF A ROTATIONALLY OSCILLATING CYLINDER"

AIAA Journal, Vol. 42, No. 6, 2004, pp. 1268-1272

The vortex wake behind a rotationally oscillating circular cylinder at $Re = 1750$ was investigated. Depending on the forcing frequency and amplitude, different vortex-shedding modes, like those observed for a cylinder in transverse and sinusoidal motion were observed. The vortex wake expanded for oscillation frequencies less than the Karman frequency whereas it contracted for frequencies greater than the Karman frequency. The longitudinal spacing decreased significantly with increasing oscillation frequency and changed to a much lesser degree with an increase in the oscillation amplitude. In contrast, the lateral spacing of the shed vortices showed a relatively weaker dependence on the rotary oscillation. Further experiments on the vortex strength and formation are needed to better understand the characteristics of the various synchronized wake patterns.

Lee, T.-C.

"NAVIER-STOKES SOLUTION OF WING WAKE STRUCTURE AND ITS PERTURBATION"

Ph.D. Thesis, January 1993, Univ. of Kansas, Lawrence, KS.

A 'flow embedding' method based on Navier-Stokes solutions is developed to calculate detailed wing wake structures. The method allows the calculation to be completed in two stages, first a global solution with a coarse grid and then the embedded solution in a small region with a dense grid. The main advantages of this two-staged scheme are: (1) it provides a very fine grid resolution in the region of interest to capture flow details; and (2) it calculates efficiently without demanding huge computer memory space. This embedded flow method, when comparing the numerical results with available experimental data in the near wake, is shown to produce a detailed and accurate wake structure for a delta wing. The computed results further downstream indicate that there are two concentrated vortices, one being the leading-edge vortex, and the other being the trailing vortex, rotating opposite to each other. These two vortices stay strong and well organized from feeding of wake shear layers. Due to this effect, the total pressure and axial velocity of both vortices are increasing in the

downstream direction. For the rectangular wing of aspect ratio 6, the calculated results are also compared with near-wake experimental data. Again, two vortices are identified, one being the conventional tip vortex and the other being the trailing vortex. The tip vortex is formed at the wing tip and moves outboard and upward; while the trailing vortex is formed downstream from the roll-up of shear layer and tends to move inboard and downward. The calculated total velocity in the core and the maximum tangential velocity around the trailing vortex core are shown to agree reasonably well with experimental data. The steady-state Navier-Stokes solution of the local wake flow region further serves as a base flow for wake attenuation investigations. An oscillatory disturbance is imposed at the trailing edge of the wing to excite the instabilities of the wake flow. Results from the unsteady computations indicate that the current scheme can excite the wake flow with limited success.

Lee, Y. L. and Gursul, I.

"AN INVESTIGATION OF UNSTEADY INTERACTIONS OF A VORTEX PAIR OVER DELTA WINGS"

AIAA Paper No. 2003-0423, Reno, NV, January 2003

An investigation of unsteady interactions of a vortex pair over stationary delta wings was carried out. Two-point measurements of unsteady flow velocity were performed to detect the unsteady interactions in a wind tunnel investigation. Response of the vortex pair to controlled antisymmetric perturbations was studied. Results show that the vortex pair does not respond to antisymmetric perturbations at low angles of attack. As incidence is increased, even before vortex breakdown appears on the wing, the vortex pair becomes responsive to the antisymmetric perturbations over a range of excitation frequencies. This range of frequencies agree very well with the theoretical predictions for an idealized point vortex pair over slender delta wings. When vortex breakdown is near the trailing-edge, largest responses were observed, indicating a coupling with antisymmetric oscillations of vortex breakdown locations.

Leese, G. W.

"UH-1H DOWNWASH VELOCITY MEASUREMENTS"

Final Report, August 1972, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi (and Misc. Paper S-72-31).

Field measurements were made to determine the velocity of the horizontal and vertical downwash flow beneath the rotor of a UH-1H helicopter. Maximum downwash velocities measured during a 7-sec period were as follows: Horizontal, 41 feet from center of rotor rotation, hover height 10 feet and 59 mph maximum downwash velocity; Vertical, 29 feet from center of rotor rotation, hover height 30 feet and 30 mph maximum downwash velocity.

Leese, G. W. and Knight Jr, J. T.

"HELICOPTER DOWNWASH DATA"

Misc PAPER S-74-17, June 1974, US Army Engineer Waterways Experimental Station, Vicksburg, MS.

The report describes an investigation involving measurement of horizontal velocities, along and up to six feet above the ground surface, generated by the rotor systems of various Army helicopters during takeoff, hover, and fly-by operations. Measurements of ground-wash velocities during various operational modes were collected for OH-58A, OH-6A, AH-1G, UH-1H, UH-1M, CH-47, and CH-54 helicopters.

Lehman, A. F.

"MODEL STUDIES OF HELICOPTER TAIL ROTOR FLOW PATTERNS IN AND OUT OF GROUND EFFECT"

USAAVLABS TR-71-12, April 1971, Oceanics Inc., Plainview, NY

Water tunnel studies of a model helicopter which entailed a visualization of the main and tail rotor wakes, the inflow patterns, and their subsequent interactions as the wind velocity and wind reading were changed are presented. Of significant interest was the impingement of the main rotor wake with a ground plane.

Leibovich, S.

"WAVE PROPOGATION, INSTABILITY, AND BREAKDOWN OF VORTICES"

Vortex Motion: Proceedings of a Colloquium Held at Goettingen on the Occasion of the 75th Anniversary of the Aerodynamische Versuchsanstalt in November 1982, edited by Hornung, H. G. and E. A. Mülle.

The themes of wave propagation and hydrodynamic stability have played prominent roles in attempts to understand the phenomenon of vortex breakdown. Recent theoretical and experimental work provide evidence that waves and instabilities are important elements of the vortex breakdown process. Breakdown of vortex cores at high Reynolds numbers may occur in one of two forms: the apparently axisymmetric ('bubble') form or the 'spiral' form. The application of soliton theory and hydrodynamic stability theory to both forms is discussed, together with a new large amplitude theory for axisymmetric waves.

Leibovich, S.

"VORTEX STABILITY AND BREAKDOWN: SURVEY AND EXTENSION"

AIAA Journal, Vol. 22, No. 9, September 1984, pp. 1192-1206

Given a model describing the smooth streamwise evolution of a vortex core, the position of breakdown may be estimated by computing the Froude number N , the stability ratio q/q_c where q_c corresponds to the critical value of q . In the observations that can be documented, stationary vortex breakdown occurs in supercritical regions, N greater than 1. The location seems to correlate better

with the point at which the vortex reaches a marginally stable condition than it correlates with the point at which critical conditions are obtained. A new conceptual framework is suggested based upon information derived from experimental studies of vortex breakdown. In the picture put forward, growth of axisymmetric modes occurs as a result of propagation in a variable vortex waveguide, and this wave loses stability to three-dimensional disturbances when it reaches a critical amplitude. Energy drain from the axisymmetric wave to the non-axisymmetric modes serves to fix the possible equilibrium positions of the vortex breakdown, which is identified with a large amplitude axisymmetric wave and smaller amplitude superposed non-axisymmetric wave modes.

Leibovich, S.

"WAVE MOTION AND VORTEX BREAKDOWN"

AIAA Paper No. 1969-0645, San Francisco, CA, 1969

Vortex breakdown is a phenomenon occurring in rotating fluids when there is a component of velocity along the axis of rotation. It occurs in many flows including the conical vortex cores above delta wings on an angle of attack, leading to an abrupt deceleration of the flow and the consequent rapid expansion of stream surfaces. In the original theory, due to Squire, it was suggested that the phenomenon was related to wave motion along the rotation axis. Squire's theory was for infinitesimal perturbations, and Benjamin pointed out a serious inconsistency which discredited the wave idea. Here the wave theory is re-examined, by considering the effects of nonzero wave amplitude. It is found that a nonlinear wave theory is consistent, is easy to calculate, and is quite flexible, allowing treatment of both incompressible and compressible fluids, in either axially-symmetric or spiral wave modes.

Leibovich, S.

"THE STRUCTURE OF VORTEX BREAKDOWN"

Annual Review of Fluid Mechanics, Vol. 10, Ann. Rev. Inc., Palo Alto, 1978, pp. 221-246

A survey of experimental and theoretical work on vortex breakdown published since the 1972 review by Hall. All studies have been carried out at low speeds so only incompressible motions are considered.

Leiden, K., Priess, S., Harrison, P., Stone, R., Palmer, M. and Strande, P.

"PAIRED APPROACH FLIGHT DEMONSTRATION: PLANNING AND DEVELOPMENT ACTIVITIES"

2018 Integrated Communications Navigation and Surveillance (ICNS) Conference, Paper 3G4, April 2018, Herndon, VA.

Simultaneous arrivals to closely spaced parallel runways (CSPR) are permissible when visual approaches can be conducted, and visual separation from the lead aircraft and its wake can be provided by the trail aircraft flight crew. During instrument meteorological conditions (IMC), CSPR

visual approaches cannot be conducted, and instrument approach procedures are used. These procedures reduce the airport capacity because of increased separation to compensate for surveillance uncertainty and larger collision avoidance response times associated with having a controller in the loop. To increase capacity during IMC, the Paired Approach procedure has been developed. The Paired Approach procedure is a part of Interval Management (IM), which leverages automatic dependent surveillance-broadcast (ADS-B) Out for the lead aircraft (referred to as the Target aircraft) and ADS-B In for the trail aircraft (referred to as the IM aircraft). During the Paired Approach procedure, the IM aircraft uses speed commands from the flight-deck IM (FIM) equipment to maintain precise spacing between itself and the Target aircraft. The IM flight crew is given a time-based spacing parameter referred to as the assigned spacing goal, which is the desired spacing behind the Target aircraft. The desired spacing between the IM and Target aircraft in a Paired Approach operation is the spacing that will keep the IM aircraft far enough behind the Target aircraft to avoid the risk of a collision while still being close enough to the Target aircraft to avoid an encounter with its wake. The FAA is conducting a Paired Approach Flight Demonstration at San Francisco International Airport in early 2019. Honeywell is developing the prototype avionics that will be used and Alaska Airlines, United Airlines, and Honeywell are providing aircraft. The FAA is choosing to scope the demonstration based on a limited part of the Paired Approach operational concept due to technology and concept maturity.

Leishman, J. G.

"MEASUREMENTS OF ROTOR TIP VORTICES USING LASER DOPPLER VELOCIMETRY"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany, pp. 449-458.

An experimental investigation has been made to study blade tip vortex structure in the wake of hovering rotors using three-component laser Doppler velocimetry. Several interesting conclusions have been drawn from the study. First, the swirl or tangential velocity profiles surrounding the tip vortices were found to be asymmetric. This is because of the curved nature of the vortices, which produces a self-induced effect. Second, for the one-bladed rotor the vortex core was found to diffuse approximately with the square-root of wake age up to the first blade passage. For the two-bladed rotor, the initial core size was somewhat larger and the tip vortices did not diffuse as quickly. However, in each case the core sizes after the first blade passage were approximately the same. Third, at the first blade passage event, a change was observed in the tip vortex diffusion because of an increase in tangential velocity and decrease in viscous core size. However, the net circulation about the vortex remained constant throughout. Fourth, the tip vortices from both rotors exhibited deficit type axial velocity profiles in their early stages, although of considerably different magnitude.

Leishman, J. G.

"SEED PARTICLE DYNAMICS IN TIP VORTEX FLOWS"

J. Aircraft, Vol. 33, No. 4, July-August 1996, pp. 823-825

Experiments and calculations have been conducted to explore issues associated with seeding of strong vortical flows for LDV measurements, such as flows induced by the tip vortices generated by rotors. Both velocity errors and statistical weighting of the seed distribution through the vortex have been examined. Radial velocity errors tend to be larger than swirl errors, and dominate up to two core radii from the vortex axis. The weighting of seed is such that the core (rotational) region suffers a scarcity of particles, with a peak in the density distribution well outside the viscous core. This distribution is very sensitive to particle mass and size. A nondimensional parameter has been developed to help quantify the likelihood of successfully seeding a typical vortex flow.

Leishman, J. G.

"UNSTEADY AERODYNAMICS OF AIRFOILS ENCOUNTERING TRAVELING GUSTS AND VORTICES"

J. Aircraft, Vol. 34, No. 6, November-December 1997, pp. 719-729

By means of the reverse flow theorems, results are obtained for the unsteady lift and pitching moment on two-dimensional airfoils penetrating sharp-edged traveling gusts. Both downstream and upstream traveling gusts are considered. For the incompressible case, exact results are given and are generalized numerically for any gust field by means of Duhamel superposition. Results are then given for the air loads and acoustics generated by a two-dimensional airfoil encountering a vortex convecting at different gust speed ratios. Numerical results for the traveling sharp-edged gust problem are also derived for subsonic flows by means of exact linear theory. Further results for the subsonic case are computed by means of an Euler finite difference method. It is found that the gust speed ratio has substantial effects on the unsteady air loads and will be an important parameter to represent in helicopter rotor aero acoustic problems.

Leishman, J. G.

"MEASUREMENTS OF THE APERIODIC WAKE OF A HOVERING ROTOR"

Experiments in Fluids, Vol. 25, 1998, pp. 352-361

An experimental investigation was made to study the aperiodic flow characteristics of the tip vortices generated by one-bladed and two-bladed hovering rotors. Measurements of the tip vortex locations and accompanying aperiodicity statistics were established as a function of vortex age. Velocity field measurements were made using three-component laser Doppler velocimetry. The average amplitude of the aperiodicity was found to be a fraction of the measured viscous core radius, this being approximately 5% of blade chord or about 50% of the core radius for wake ages of less than two rotor revolutions. The aperiodicity appeared isotropic. A numerical analysis of the aperiodicity problem based on convolution with an assumed displacement probability function showed that for this experiment the measured tangential velocities in the tip vortices were underestimated by approximately 20%. There was no evidence that the number of blades or the blade passage adversely influenced the aperiodicity of the rotor tip vortices.

Leishman, J. G.

"INTRODUCTION: ROTOR WAKES"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, p. 721.

This special issue of the Journal of Aircraft concerns the improved understanding and prediction of rotor wake aerodynamics of helicopters and tilt rotors. This task continues to be of fundamental importance in defining blade aerodynamics, and in evaluating new and improved rotor designs that are more efficient in hover and forward flight, show lower vibration levels, and are also acoustically quieter. As this special issue shows, the field of rotorcraft aerodynamics, particularly the subject of rotor wakes, will continue to challenge the rotorcraft analysts of the future with some of the most fascinating problems in fundamental fluid dynamics and applied aerodynamics.

Leishman, J. G. and Bagai, A.

"CHALLENGES IN UNDERSTANDING THE VORTEX DYNAMICS OF HELICOPTER ROTOR WAKES"

AIAA Journal, Vol. 36, No. 7, July 1998, pp. 1130-1140

Many experimental challenges are encountered when attempting to understand the complex vortical wakes generated by helicopter rotors. The problems are illustrated by means of several examples, including blade/vortex interactions, vortex perturbations, wake instabilities, and vortex/surface interaction phenomena. Specific emphasis is placed on flow visualization and quantitative measurements using laser Doppler velocimetry.

Leishman, J. G. and Martin, P. B.

"MEASUREMENTS OF THE TRAILED VORTEX WAKE FROM A HELICOPTER ROTOR"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Improved helicopter designs require a much better understanding of the flow physics produced by the intense wake vortex system generated by the main rotor. A helicopter rotor wake is known to be highly dynamic, vortical, and three-dimensional in nature, being comprised mostly of intertwining tip vortices generated by the blades. These tip vortices may remain close to the rotor plane as localized, coherent flow structures for several rotor revolutions after they are generated. The present work reports on high-resolution three-dimensional velocity-field measurements and flow visualization results that were acquired in the wake of a sub-scale helicopter rotor blade. Using three-component laser Doppler velocimetry (LDV), the measurements documented the trailing tip vortex formation, its initial structure, and the viscous evolution of the vortex core. The test conditions covered a range of wake-ages from as young as one-degree, up to about one rotor revolution. For each wake age, vortex core properties were estimated from the velocity-field measurements. The high spatial and temporal resolution of the measurements (obtained, in part, through a precise alignment of the LDV optics using a laser beam profiler) has shown that the tip vortex core radius can be less than 3% of chord just at

formation, but grows asymptotically as it ages. A significant axial velocity deficit was found in the vortex core, which was of the order of the peak swirl velocity at early wake-ages but quickly diminished as the tip vortex aged. Using a Richardson parameter combined with strobed laser light-sheet visualization of the tip vortex flow, the results suggest that the inner core of the tip vortex is mostly laminar at the vortex Reynolds numbers obtained in this experiment. It was found that bands of turbulent eddies, originating from an adjacent vortex sheet trailed by a blade, underwent a relaminarization process as they were entrained into the vortex core. The evidence suggests that the entire tip vortex structure is neither fully laminar or fully turbulent, but is instead in a continuous state of dynamic evolution with a region of relatively slow laminar diffusion and a region of accelerated turbulent diffusion. It is suggested that the variation of peak swirl velocity is the result of the competing influences of an inviscid roll-up process and viscous diffusion within the tip vortex.

Leishman, J. G., Bhagwat, M. J. and Ananthan, S.

"FREE-VORTEX WAKE PREDICTIONS OF THE VORTEX RING STATE FOR SINGLE-ROTOR AND MULTI-ROTOR CONFIGURATIONS"

58th Annual Forum, American Helicopter Society, June 2002, Montreal, Canada.

Results are shown that give a better understanding of factors that may influence the initiation and subsequent development of the vortex ring state (VRS) on single rotors, tandems, and laterally side-by-side (tiltrotor) configurations. This problem is approached from the perspective of vortex wake theory and a wake stability analysis. The results show that for all types of rotors operating in hover or at low rates of descent, the rotor wake is inherently unstable. Increasing the descent velocity makes the wake more susceptible to developing instabilities, which causes the regular helicoidal form of the wake to break down. Eventually, higher rates of descent take the rotor into the beginnings of the VRS, the onset of which occurs when wake instabilities reach the rotor disk. The low net velocity near the rotor at these higher rates of descent causes vorticity to accumulate near the rotor plane, forming tight bundles resembling vortex rings. This is an unstable flow condition, where the rings develop Kelvin waves and periodically break away from the rotor disk, leading to the aperiodic fluctuations of blade air loads and rotor thrust that is characteristic of the VRS. The results show that the wake breakdown and onset of VRS depends on several factors that are a consequence of rotor configuration, and as well as the rotor operating state. Maneuvering flight issues are also shown to be significant factors that can affect the conditions for wake breakdown. The vortex wake characteristics of the tiltrotor configuration is investigated in some detail because of the significant asymmetric interactions that can occur between the two rotor wakes when in descending flight.

Leishman, J. G., Bhagwat, M. J. and Ananthan, S.

"THE VORTEX RING STATE AS A SPATIALLY AND TEMPORALLY DEVELOPING WAKE INSTABILITY"

American Helicopter Society International Specialists Meeting on Aerodynamics, Acoustics and Test and Evaluation, San Francisco, CA, January 2002

It is shown that the onset and development of the vortex ring state (VRS) on a rotor can be viewed as a spatial and temporal wake instability. A linearized wake stability (eigenvalue) analysis and a second-order-time accurate free-vortex method are used to show that the flight conditions leading to the onset of wake instabilities are rotor configuration and operating state specific. In hovering flight the rotor wake is shown to be in unstable equilibrium, and the wake stability increases with climb rate. However, in descending flight the wake is shown to be more susceptible to the onset and persistence of instabilities because of the reduced helicoidal spacing between the individual vortex filaments. The results suggest that equilibrium descending flight conditions can be reached when wake instabilities are being formed as quickly as they are being convected away from the rotor. A slightly greater rate of descent then takes the rotor into the beginnings of the VRS, the onset of which occurs when disturbances produced by the wake instabilities reach the rotor disk. Under these conditions, the rotor wake may recirculate in the rotor plane as individual tip vortices form tight bundles of vorticity resembling vortex rings. These rings are spatially and temporally unstable, and break away from the rotor disk leading to the aperiodic fluctuations of blade air loads and rotor thrust that are characteristic of the VRS. The results suggest that subtle differences in the onset of VRS are a consequence of rotor configuration and operating state. Side-by-side rotor configurations are shown to have interesting asymmetric VRS characteristics resulting from mutual interactions between the two rotor wakes, the onset of which occurs at relatively low rates of descent.

Leishman, J. G., Bhagwat, M. J. and Bagai, A.

"FREE-VORTEX FILAMENT METHODS FOR THE ANALYSIS OF HELICOPTER ROTOR WAKES"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 759-775

The theoretical basis and the numerical implementation of free-vortex filament methods are reviewed for application to the prediction and analysis of helicopter rotor wakes. The governing equations for the problem are described, with a discussion of finite difference approximations to these equations and various numerical solution techniques. Both relaxation and time-marching wake solution techniques are reviewed. It is emphasized how the careful consideration of stability and convergence (grid-independent behavior) are important to ensure a physically correct wake solution. The implementation of viscous diffusion and filament straining effects are also discussed. The need for boundary condition corrections to compensate for the inevitable wake truncation are described. Algorithms to accelerate the wake solution using velocity field interpolation are shown to reduce computational costs without a loss of accuracy. Several challenging examples of the application of free-vortex filament methods to helicopter rotor problems are shown, including multirotor configurations, flight near the ground, maneuvering flight conditions, and descending flight through the vortex ring state.

Leishman, J. G., Martin, P. B. and Pugliese, G. J.

"SURFACE AND WAKE FLOW CHARACTERISTICS OF A HOVERING HELICOPTER ROTOR"

9th International Symposium on Flow Visualization, Paper No. 189, 2000, pp. 189-1-189-10

Surface flow visualization methods were examined for potential application to a hovering helicopter rotor blade. These techniques included liquid crystals, chemical sublimation, and fluorescent oil flow. Test cases involved both the identification of a laminar separation bubble and the effects of a serrated boundary layer trip strip. The results were used to understand some of the boundary layer physics associated with sub-scale helicopter rotor testing. In addition, the vortex system trailed into the wake behind the rotor blades was studied using laser sheet smoke flow visualization. The results were supported by quantitative measurements of the flow made using LDV and PIV.

Lele, S. K.

"VORTEX-WAKE POLLUTION: A PROBLEM IN FLUID MECHANICS"

Lecture Notes in Physics, Vol. 566, 2001, pp. 163-181.

The vortex-wake of an airplane contains a system of one or more pairs of trailing vortices. The vortex-wake interacts with the surrounding atmosphere and decays due to instabilities such as the Crow instability. The downwash associated with the wake constitutes a hazard to other airplanes since it may cause an appreciable loss of lift and/or induce a rolling-moment. This can be dangerous if the second airplane is near the ground such as during takeoffs and landings. In this paper we begin by drawing parallels between this problem of air-space pollution near airports due to vortex-wakes and other environmental pollution problems. Attention is focused on how fluid mechanical processes influence different elements of this problem and on fluid mechanical means with potential of alleviating the wake hazard.

Lemonis, G., Schmucker, M. and Struck, H.

"A FAST RESPONSE PROBE SYSTEM FOR IN-FLIGHT MEASUREMENTS OF ATMOSPHERIC TURBULENCE"

Aerospace Science and Technology, Vol. 6, 2002, pp. 233-243.

A fast response probe for in-flight, three-dimensional measurements of atmospheric turbulence is presented. The system comprises a commercial five-hole probe connected to miniature pressure transducers by extremely short pneumatic lines. This design yields high dynamic response with negligible transmission errors at least up to 10 Hz. The transducers are installed into a temperature-conditioned shell to eliminate thermal zero and sensitivity shifts during flight. The system has been tested on the Falcon D-CMET research aircraft of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) in Oberpfaffenhofen at flight altitudes up to 37000 ft (11278 m) and Mach numbers up to 0.75. Spectral analyses of the air-data obtained by the system confirm the predictions concerning its high frequency response capabilities. Simultaneous measurements with conventional air sensing devices installed in the aircraft provide evidence regarding the operational reliability and the accuracy of the system.

Lengendre, R.

"EFFECT OF WING TIP SHAPE ON VORTEX SHEET ROLLING UP"

Rech. Aerosp., No. 4, July-August 1971, pp. 227-228

Laws of separation over a whole wing are applied to study straight or moderately swept back wings. The effect of vortex sheet rolling up can be avoided by tailoring the profile of the trailing edge to the edge of a wing or blade, with constant or zero leading edge sweepback, in such a way as to make a clear distinction between the leading and trailing edges. Break phenomena are studied.

Lennert, A. E., Crosswy, F. L. and Kalb, H. T.

"APPLICATION OF THE LASER VELOCIMETER FOR TRAILING VORTEX MEASUREMENTS"

AEDC-TR-74-26, December 1974, ARO Inc., Arnold Air Force Station, TN

This report summarized a three-year analytical and experimental program to develop a dual-scatter laser velocimeter system to map the flow field of trailing vortices stemming from the wingtips of flying aircraft. The basic design parameters ascertaining feasibility of the LV-measuring technique are presented. Included is a discussion and evaluation of a newly developed two-dimensional Bragg cell for resolving directional ambiguity. The electronics instrumentation developed for the operation of the Bragg cell is evaluated in detail.

Leonard, A.

"VORTEX METHODS FOR FLOW SIMULATION"

Journal of Computational Physics, Vol. 37, 1980, pp. 289-335.

Recent progress in the development of vortex methods and their applications to the numerical simulation of incompressible fluid flows are reviewed. Emphasis is on recent results concerning the accuracy of these methods, improvements in computational efficiency, and the development of three-dimensional methods. Simulations of several example flows which display some of the strengths and weaknesses of vortex methods are presented.

Leopold, F., Jagusinski, F. and Demeautis, C.

"EXPERIMENTAL INVESTIGATION OF SHOCK/VORTEX INTERACTION FOR SLENDER CANARD CONFIGURATION AT SUPERSONIC SPEED"

Proceedings 20th International Congress on Instrumentation in Aerospace Simulation Facilities 2003, Gottingen, Germany, August 25-29, 2003, pp. 247-257

The interaction of a concentrated vortex and a shock wave may occur in many cases in the operational environment of supersonic aircraft and missiles. The interaction may be the result of vortices created by the forward components of a supersonic vehicle (for example canards, wings, etc.)

convecting downstream and interacting, for example, with shock waves present in front of air intakes or other wings. The objective of the present work is to conduct experimental studies simulating the interaction of streamwise wing-tip vortices with shock waves in supersonic flows. Flow-field visualizations show the different behavior (for example: unsteady vortex breakdown). To elucidate the complex flow containing shock waves, backflow and large-scale fluctuations, measurements using a laser Doppler velocimeter (LDV) were carried out.

Leopold, F., Richard, H., Raffel, M. and Christnacher, F.

"EXPERIMENTAL INVESTIGATIONS OF THE INTERACTION OF SUPERSONIC WING-TIP VORTICES WITH A NORMAL SHOCK"

11th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 2002

The interaction of a concentrated vortex with a shock wave may occur in many instances in the operational environment of supersonic aircraft and missiles. The interaction may be the result of vortices created by the forward components of a supersonic vehicle convecting downstream and interacting, for example, with shock waves present in front of air intakes or other wings. The objective of the present work was to conduct an experimental study simulating the interaction of streamwise wing-tip vortices with normal shock waves in a Mach 3 flow. Therefore, an experimental study was conducted to simulate the interaction of streamwise wing-tip vortices and normal shock waves. In this paper two recently developed visualization techniques are shown. The results of the Background Oriented Scattering (BOS), invented at DLR, are compared to the flow-field visualizations, obtained by using the ISL holographic filters. To elucidate the complex flow containing shock waves, backflow and large-scale fluctuations, measurements using a laser Doppler velocimeter (LDV) were carried out.

Leppington, F. G.

"THE FIELD DUE TO A PAIR OF LINE VORTICES IN A COMPRESSIBLE FLUID"

J. Fluid Mech., Vol. 559, 2006, pp. 45-55

The problem considered is that of a self-propagating pair of line vortices, of equal and opposite strengths, in a compressible inviscid fluid. An asymptotic solution is sought in the limit of small propagation speed compared with the sound speed in the medium. In most of the fluid region, the elementary incompressible flow solution limit is enhanced by a Rayleigh-Janzen approximation. This approximation fails at points that are either far from, or very close to, a vortex. For distant points, rescaled outer variables lead to an approximation that corresponds to the field induced by a moving dipole in compressible fluid. The main approximation also fails near each vortex line, where the analysis of Barsony-Nagy, Er-el & Yungster (J. Fluid Mech. Vol. 178, 1987, p. 367) is used to express the local flow field in terms of a hypergeometric function.

Leroy, A., Buron, F. and Devinant, P.

"UNSTEADY AERODYNAMIC MODEL FOR THIN WINGS WITH EVOLUTIVE VORTEX SHEETS"

RTO AVT Symposium on 'Advanced Flow Management: Part A - Vortex Flows and High Angle of Attack for Military Vehicles', Loen, Norway, May 2001.

This paper presents recent advances in a computing method for unsteady inviscid incompressible flows around thin lifting surfaces with arbitrary motion. This involves the velocity field, deriving from a potential, the pressure field, and the free vortex sheet characteristics (geometry and vortex strength). When considering high angles of attack, the separation lines along which the vortex sheets are shed are the trailing edge, as well as wing tips or parts of the leading edge. Compared to classical methods of singularity, such as panel methods, an improved vortex wake model was constructed. It consists in representing the wake by a vortex particle concept, particularly well-suited for the prediction of its unsteady deformations. This approach stems from the unsteady vortex sheet theory established by MUDRY, in which the vortex sheet is considered as a median layer, on which is founded the concept of continuous vortex particle. This ensures the computing method to compare favorably with the classical methods in terms of flexibility and computing costs. Computed unsteady flow-field simulations are presented for several cases and compared with some available experimental data.

Leroy, A., Molton, P., Carpels, Y. and Pons, J.

"EXPERIMENTAL STUDIES OF DBD ACTUATOR EFFECTS ON WING TIP VORTEX TOPOLOGY"

AIAA Paper No. 2012-2951, June 2012, New Orleans, LA.

Experiments studying the wing tip vortex, generated by a rectangular wing with a symmetric airfoil section and a straight tip, manipulated by surface plasma actuators are presented in this paper. Objectives are focused on modifying vortex development to alter streamwise vorticity downstream of the wing trailing edge. Actual limitation of the ionic wind magnitude obtained with DBD actuators leads to investigate vortex control by action on the transverse component of the freestream flow velocity. Different DBD arrangements installed near the wing tip were tested to examine effects of momentum addition, firstly on the pressure and suction side surfaces, and secondly, simultaneously located more precisely on the main vortex separation and attachment lines. Stereoscopic PIV measurements were performed in different planes orthogonal to the vortex development axis to visualize and characterize wing tip vortices. According to DBD arrangements, results of the actuation show a slight displacement of the wing tip vortex and a reduction of the mean streamwise vorticity level in its core.

Lesieutre, D. J. and Quijano, O.

"STUDIES OF VORTEX INTERFERENCE ASSOCIATED WITH MISSILE CONFIGURATION"

AIAA Paper 2014-0213, January 2014, National Harbor, MD.

Studies of vortex-induced aerodynamic nonlinearities associated with body and fin vortices for missile configurations have been performed. As part of this effort, the vortex and fin modeling methodologies in the engineering-level and intermediate-level aerodynamic predictions codes MISL3 and MISLDL have been reviewed and improved. The ability of the methods to predict detailed fin loads in the presence of external vortices is demonstrated. Both codes have been used extensively to predict missile performance including canard/wing vortex induced effects on tail fins. These effects often manifest themselves in pitching moments and most dramatically in induced rolling moments on tail fins which counter, and often times reverse, the direct roll control of canard fins. Both codes have shown the capability to capture these vortex-induced phenomena. For validation purposes, the methods were compared to detailed vortex-fin interaction studies, performed at Sandia National Laboratories, which measured fin loads influenced by a vortex generated by an upstream fin.

Leslie, F. W. and Justus, C. G.

"THE NASA MARSHALL SPACE FLIGHT CENTER EARTH GLOBAL REFERENCE ATMOSPHERIC MODEL-2010 VERSION"

NASA TM-2011-216467, June 2011, NASA Marshall Space Flight Center; Huntsville, AL.

Reference or standard atmospheric models have long been used for design and mission planning of various aerospace systems. The NASA Marshall Space Flight Center Global Reference Atmospheric Model was developed in response to the need for a design reference atmosphere that provides complete global geographical variability and complete altitude coverage (surface to orbital altitudes), as well as complete seasonal and monthly variability of the thermodynamic variables and wind components. In addition to providing the geographical, height, and monthly variation of the mean atmospheric state, it includes the ability to simulate spatial and temporal perturbations.

Lessen, M.

"METHOD AND APPARATUS FOR ELIMINATION OF AIRFOIL TRAILING VORTICES"

US Patent 3,881,669, May 1975

Herein are disclosed a method and apparatus for eliminating or substantially attenuating the dangerous vortices which typically trail the airfoils of heavier-than-air aircraft in flight. The disclosed method consists of injecting a fluid stream into the core of the vortex (a) in a direction such that the longitudinal axis of the injected fluid stream is substantially colinear and coaxial with the longitudinal axis of the vortex where the injected stream enters the vortex core, and (b) at a momentum flux of such magnitude relative to that of the free air stream that the vortex will be rendered hydrodynamically unstable. The criteria as to the direction and the magnitude of the momentum flux of the injected fluid stream are disclosed as critical to the successful practice of the invention. It is preferable that the departure from co-linearity be not more than 4 degrees. The apparatus of the invention comprises, in combination with an airfoil, a pair of nozzles adapted for injecting a fluid stream of the required orientation and of a momentum flux of such magnitude relative to the free air stream

into the trailing vortex that the trailing vortex will be rendered hydrodynamically unstable and apparatus for supplying a suitable fluid to the nozzles.

Lessen, M.

"THE HYDRODYNAMIC STABILITY OF A TRAILING VORTEX"

Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, Air Force Flight Dynamics Laboratory, AFFDL-TM-75-16-FGC, 1974, pp. 37-41

The results of research being conducted at the University of Rochester on the hydrodynamic stability of swirling flows was presented. There are two basic aspects to the problem: the mathematical solution of the formalized stability theory as applied to wake vortex models, and the extension of results obtained in such investigations to the finite amplitude disturbances and fully turbulent flows encountered in real life.

Lessen, M.

"AMELIORATION OF TRAILING VORTICES VIA INJECTION"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 19-1 - 19-11

The assumptions underlying the calculation of the turbulent trailing line vortex and the principle of marginal instability are examined. The similarity solution for the turbulent trailing vortex is developed and the power laws derived. The inviscid stability of the vortex is studied and the maximum swirl ratio for instability is obtained analytically.

Lessen, M. and Paillet, F.

"THE STABILITY OF A TRAILING LINE VORTEX, PART 2: VISCOUS THEORY"

J. Fluid Mech., Vol. 65, Part 4, October 1974, pp. 769-77.

The viscous stability of the Lamb vortex and axisymmetric wake is explored. A locally constant eddy viscosity is used to formulate the full stability equations. Disturbance growth rates are then calculated as a function of Reynolds number, axial and azimuthal periodicity, and intensity of core rotation. It is shown that the initial destabilization by the superposition of stable rotation reduces the minimum critical Reynolds number to half that for the wake alone. All modes are stabilized when the rotation becomes strong, and the increase of minimum critical Reynolds number with increasing rotation is traced.

Lessen, M., DeShpande, N. V. and Hadji-Ohanes, B.

"STABILITY OF A POTENTIAL VORTEX WITH A NON-ROTATING AND RIGID-BODY ROTATING TOP-HAT JET CORE"

J. Fluid Mech., Vol. 60, Part 3, September 1973, pp. 459-466

The stability of a potential vortex with a rotating and a non-rotating jet core is analyzed. Eigenvalues are calculated numerically for different values of the ratio of the strength of the vortex to the axial velocity. These results show that the potential vortex becomes unstable in the presence of a jet.

Lessen, M., Singh, P. and Paillet, F.

"THE STABILITY OF A TRAILING LINE VORTEX, PART 1: INVISCID THEORY"

J. Fluid Mech., Vol. 63, Part 4, May 1974, pp. 753-76.

The hydrodynamic stability of a continuous velocity distribution (Lamb vortex and axisymmetric wake) resembling that in a wake vortex is examined, and stability is calculated as a function of the ratio of maximum velocity defect to maximum tangential flow. It is found that rotation can destabilize the axisymmetric wake, but that all instability modes appear stable when the rotation becomes strong enough.

Leuchter, O. and Solignac, J. L.

"EXPERIMENTAL INVESTIGATION OF THE TURBULENT STRUCTURE OF VORTEX WAKES"

4th Symposium sur les Ecoulements Cisailles Turbulents, University of Karlsruhe, September 1983

Two configurations of vertical wake flows are investigated. The first (flow A) corresponds to a double branched trailing vortex, the second (flow B) to the leading-edge vortex of a delta wing. Both flows are studied in the presence of a destabilizing adverse pressure gradient leading to vortex breakdown. For various degrees of destabilization, the flow field is explored by means of a two-color laser velocimeter that yields mean velocity and Reynolds stress distributions across the flow. Breakdown is characterized by a strong deceleration of the flow near the axis of the vortex, by a significant decrease of the rotation rate in the center and consequently by a large production of turbulence. When breakdown occurs, both types of flow reveal similar characteristics of the flow structure. However, there are also significant differences, the most important being the abruptness of the breakdown phenomenon and its instability character which is much more pronounced for vortex flow B.

Leung, R. C. K. and Ko, N. W. M.

"THE INTERACTION OF PERTURBED VORTEX RINGS AND ITS SOUND GENERATION"

Journal of Sound and Vibration, Vol. 202, Issue 1, April 1997, pp. 1-27

Interactions of two coaxial vortex rings of thin cores with and without azimuthal instability and the far field sound radiated have been studied numerically using the vortex blob method and acoustic analogy. The azimuthal instability waves of wavenumbers m less than or equal to 5 or greater than or equal to 1 are represented by weak axial and radial sinusoidal perturbations. It was found that the behavior and the far field sound radiated of two perturbed vortices during the three slip throughs of m less than or equal to 4 or greater than or equal to 3 and during the first slip through of m less than or equal to 5 or greater than or equal to 1 are the same as those of unperturbed case $m = 0$. Because of their mutual induction, an unstable mode of the trailing vortex is found during the third slip through at $m = 1$ and 5, significantly lower wavenumbers compared with those of a single vortex ring. The far field sound radiated and their directivity, though still quadrupole, are different from those of unperturbed cases, showing the effect of perturbation on the interaction of the two vortices. A criterion for the onset of unstable mode is also established.

Leung, R. C. K. and Ko, N. W. M.

"ON SOUND RADIATED FROM A PERTURBED VORTEX RING"

Acta Mechanica, Vol. 146, 2001, pp. 43-58.

An analysis of the evolution and sound radiation of a slender vortex ring with initial weak perturbation in free space has been done. Depending on the integer wavenumber of perturbation, the circulation and the core size of the vortex ring, the perturbation evolves in either stable or unstable modes. Both stable and unstable evolutions radiate sound in the far field, and the vortex acceleration of the vortex has been found to be a major sound radiation mechanism. A stably perturbed vortex ring radiates stronger sound than an unstable one. The finding of the present study explains some experimental observations of sound from an isolated vortex ring.

Leverton, J. W.

"IMPROVING AIRPORT CAPACITY USING VERTICAL FLIGHT"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

A new, innovative solution must be developed and implemented which makes use of the parts of the airspace system and airport infrastructure that are currently either not used or under-utilized. The use of vertical flight in the form of new generation advance technology rotorcraft, civil tiltrotor (CTR) aircraft offers this potential. These and other runway independent aircraft (RIA), using an ATC framework which allows simultaneous non-interfering (SNI) operations, would appear to be the only viable solution to the current problems if the needs of the traveling public and commerce are to be met. This is possible since significant portions of flights, particularly in the USA, are over ranges of 100 to 200 miles. These aircraft only carry a small portion of the total number of passengers but require the same airspace and runway slot as a large long-distance aircraft. These operations could easily be replaced by advanced technology rotorcraft. With the advent of CTR and other RIA ranges of up to 400

to 600 miles could similarly be handled. These have the advantage of not requiring a valuable 'slot' and could easily make use of the unused airspace (airspace 'voids') on the side of most major airports. High reliability, all weather operations including flights in icing conditions to achieve true IFR operations, is essential. Operating costs are inherently higher than today's civil flights and the need to offset such costs, together with important aspects such as flight safety (included perceived safety) environmental impact and passenger acceptance are important. Advance technology rotorcraft CTR's and RIA's offer a solution in the short term of overcoming the airport/airspace capacity limitations and providing the basis of a valuable integrated aviation system based on today's civil aviation fleet supplemented with a vertical flight segment.

Levinsky, E. S. and Strand, T.

"A METHOD FOR CALCULATING HELICOPTER VORTEX PATHS AND WAKE VELOCITIES"

AFFDL TR-69-113, July 1970, Air Vehicle Corp., San Diego, CA

A simple method is developed for calculating the time-average velocity field induced at large distances from the rotor by a helicopter in steady horizontal motion. The influence of the ground plane and of horizontal winds on the rotor wake and velocity field is included.

Levy, R. and Lin, S. J.

"USER'S GUIDE: TIP VORTEX COMPUTER CODE SRATIP"

NASA-CR-172603, July 1985, Scientific Research Associates, Glastonbury, CT

The User Guide applies to the three-dimensional viscous flow forward marching analysis as used for the calculation of the helicopter tip vortex flow field. The Guide presents a discussion of the program flow and subroutines, as well as a list of input and output.

Leweke, T.

"EXPERIMENTS ON SHORT-WAVE INSTABILITIES IN VORTEX PAIRS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Experimental results concerning the short-wavelength instability in pairs of counter-rotating or co-rotating vortices will be presented. The former is a simplified model of the far wake behind a transport aircraft, whereas the latter represents the vortex configuration in the near wake behind a single wing in high-lift configuration (lowered flap). Pairs of uniform parallel vortices were generated in water by the impulsive motion of two flat plates, and their evolution was followed in time, using dye visualizations and Particle Image Velocimetry. At sufficiently high Reynolds numbers, both flows, counter- and co-rotating pairs, were found to develop a three-dimensional instability, whose axial wavelength scales on the vortex diameter, and which is associated with internal deformations of the vortex cores. The spatial

structure of the amplified perturbations show characteristic features of elliptic instability occurring in strained vortical flows, and quantitative measurements of wavelength, radial structure, and instability growth rates are in good agreement with predictions from elliptic instability theory. In the case of counter-rotating vortices, the late stages of the instability are characterized by a strong interaction of the two vortices. Secondary structures develop and lead to a pronounced exchange of fluid between the two sides of the flow. Consequently, the average circulation in each half-plane is found to drop significantly in a short time interval, an effect which is still enhanced by the interaction with the long-wavelength Crow instability always developing simultaneously in this flow. In the co-rotating vortex pair, the short-wave instability interacts with and perturbs the process of merging into a single vortex, which is the basic (two-dimensional) phenomenon characterizing this flow. Measurements show that, in the presence of the instability, merging is initiated earlier (i.e. for smaller relative core sizes), and leads to a more turbulent final vortex than in the two-dimensional case.

Leweke, T. and Williamson, C. H. K.

"THE LONG AND SHORT OF VORTEX PAIR INSTABILITY"

Physics of Fluids, Vol. 8, No. 9, Sept. 1996, p. S5

Photographs show visualizations of different instabilities of a pair of straight counter-rotating vortices. The vortex pair is generated at the sharpened edges of two flat plates, hinged to a common base and moved in a prescribed symmetric way. Visualization is achieved using fluorescent dye.

Leweke, T. and Williamson, C. H. K.

"LONG-WAVELENGTH INSTABILITY AND RECONNECTION OF A VORTEX PAIR"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

We present new experimental results concerning the dynamics of a pair of parallel counterrotating vortices. This flow provides a prototype system for the study of elementary interactions of slender vortices. In addition, a strong link to engineering applications exists, since similar flow structures are found in the far wake of aircraft and play an important role in flight safety at airports. In this presentation we will concentrate on one of several different features we observed in this flow: a long-wavelength instability and the associated phenomenon of vortex reconnection occurring in the long-time development of this instability. Although analytical studies of vortex pairs have considered such an instability (e.g. Crow), it is surprising that neither detailed quantitative measurements nor even a clear demonstration of such structure in laboratory experiments can be found in the literature. The same applies to the study of vortex reconnection or cross-linking, which has mainly been investigated via numerical simulations.

Leweke, T. and Williamson, C. H. K.

"EXPERIMENTS ON THE SHORT-WAVE INSTABILITY OF TRAILING VORTICES"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

We present results from an experimental study of the dynamics of a pair of parallel counterrotating vortices at low Reynolds number. The flow is studied in water, where the initially two-dimensional vortices are generated by the controlled motion of two flat plates. We observe the existence of several three-dimensional instabilities with different axial wavelengths and symmetry properties. Here, we focus on a short-wave instability, which occurs above a threshold Reynolds number. It is associated with internal deformations of the vortex cores at wavelengths of less than one vortex spacing. Detailed analysis of the spatial structure of the instability mode, as well as measurements of its growth rate, show that this behavior is a consequence of a so-called elliptic instability of the vortex cores, which can be related to the short-wave instability predicted by Widnall et al. The late stages of this instability involve the inception of perpendicular secondary vortex pairs, which, in combination with the long-wavelength Crow instability, results in a very effective destruction of the large-scale vortex structures.

Leweke, T. and Williamson, C. H. K.

"THREE-DIMENSIONAL DYNAMICS OF A COUNTERROTATING VORTEX PAIR"

8th International Symposium on Flow Visualization, Sorrento, Italy, 1998, pp. 271.1-271.9

In this paper, we present results from an experimental study of the dynamics of a pair of parallel counterrotating vortices, which is uniform in the axial direction. We observe the existence of three-dimensional instabilities at different axial wavelengths, depending on the Reynolds number of the flow. Under the effect of a long-wavelength Crow instability, the vortices develop a growing waviness, leading eventually to the formation of periodic vortex rings. A short-wavelength instability, which occurs above a threshold Reynolds number and can be associated with an elliptic instability of the vortex cores, causes internal deformations of the vortices and, in combination with the Crow instability, leads to a faster decay of the large-scale vortical structures. Detailed visualizations of both phenomena are shown.

Leweke, T. and Williamson, C. H. K.

"THREE-DIMENSIONAL INSTABILITIES OF A COUNTERROTATING VORTEX PAIR"

Lecture Notes in Physics, Vol. 555, 2000, pp. 221-230

Results from an experimental investigation on the dynamics and persistence of instabilities in a counter-rotating vortex pair are presented. Two distinct three-dimensional instabilities in the flow have been observed in these tow-tank experiments, and they were visualized with laser-induced fluorescent dye and quantified with Particle Image Velocimetry. In the case of the long-wave length Crow instability, the vortices undergo a wavy deformation before they cut and reconnect into a series of large-scale vortex rings. At higher Reynolds numbers, a second short-wavelength instability appears, which leads to internal deformations of the vortices and can be explained by an elliptic instability of the vortex cores. In the presence of short waves, the long-term evolution of the pair is distinctly altered:

the average propagation speed of the vortex system decreases drastically, and the large-scale vortical structures are destroyed much more effectively than in the case of a pure Crow instability.

Leweke, T. and Williamson, C. H. K.

"COOPERATIVE ELLIPTIC INSTABILITY OF A VORTEX PAIR"

J. of Fluid Mech., Vol. 360, April 1998, pp. 85-119

In this paper, we investigate the three-dimensional instability of a counter-rotating vortex pair to short waves, which are of the order of the vortex core size, and less than the inter-vortex spacing. Our experiments involve detailed visualizations and velocimetry to reveal the spatial structure of the instability for a vortex pair, which is generated underwater by two rotating plates. We discover, in this work, a symmetry-breaking phase relationship between the two vortices, which we show to be consistent with a kinematic matching condition for the disturbances evolving on each vortex. In this sense, the instabilities in each vortex evolve in a coupled, or cooperative, manner. Further results demonstrate that this instability is a manifestation of an elliptic instability of the vortex cores, which is here identified clearly for the first time in a real open flow. We establish a relationship between elliptic instability and other theoretical instability studies involving Kelvin modes. We note that the perturbation shape near the vortex centers is unaffected by the finite size of the cores. We find that the long-term evolution of the flow involves the inception of secondary transverse vortex pairs, which develop near the leading stagnation point of the pair. The interaction of these short-wavelength structures with the long-wavelength Crow instability is studied, and we observe significant modifications in the longevity of large vortical structures.

Leweke, T. and Williamson, C. H. K.

"EXPERIMENTS ON LONG-WAVELENGTH INSTABILITY AND RECONNECTION OF A VORTEX PAIR"

Physics of Fluids, Vol. 23, 2011, pp. 024101-1 - 024101-14.

We present results from an experimental study of the long-wavelength 'Crow' instability of a counter-rotating vortex pair. Employing a vortex generator in a water tank, comprising rotating horizontal computer-controlled flaps, we follow the vortices, marked by laser-induced fluorescence, using dual simultaneous light-sheets to determine the growth rate of the Crow instability as a function of the perturbation wavelength. To make a meaningful comparison to theory, one requires, as input to the theory, the distribution of circumferential velocity and thereby the 'equivalent' core size of the vortices. These distributions are measured using particle image velocimetry. The resulting agreement of the growth rates, between theory and experiment, appears to be very good. Of relevance to this study, we compute a stability diagram using the exact expression for the self-induced rotation speed of the perturbation waves on the vortices. Measurement of the nondimensional reconnection time, when the

vortex pair evolves into a series of rings at later times, is compared to existing numerical simulations, and we find evidence to suggest it varies with the inverse curvature of the vortices where they approach each other. The major axes of the resulting elliptical vortex rings switch with their minor axes, as the rings descend in the fluid, leading to a surprising phenomenon where the rings reconnect for the second time. By considering the conservation of impulse, and a linear relationship between the major axis length and the vortex spacing, we find that the relative descent speed of the rings increases with Reynolds number. It is coincidentally only at our chosen value that the descent speed of the subsequent rings appears to be close to the initial speed of the vortex pairs. Finally, the paper presents clear visualizations of the Crow instability phenomenon.

Leweke, T., Le Dizes, S. and Williamson, C. H. K.

"DYNAMICS AND INSTABILITIES OF VORTEX PAIRS"

Annual Review of Fluid Mechanics, Vol. 48, 2016, pp. 507-541.

This article reviews the characteristics and behavior of counter-rotating and corotating vortex pairs, which are seemingly simple flow configurations yet immensely rich in phenomena. Since the reviews in this journal by Widnall (1975) and Spalart (1998), who studied the fundamental structure and dynamics of vortices and airplane trailing vortices, respectively, there have been many analytical, computational, and experimental studies of vortex pair flows. We discuss two-dimensional dynamics, including the merging of same-sign vortices and the interaction with the mutually induced strain, as well as three-dimensional displacement and core instabilities resulting from this interaction. Flows subject to combined instabilities are also considered, in particular the impingement of opposite-sign vortices on a ground plane. We emphasize the physical mechanisms responsible for the flow phenomena and clearly present the key results that are useful to the reader for predicting the dynamics and instabilities of parallel vortices.

Leweke, T., Meunier, P., Laporte, F. and Darracq, D.

"CONTROLLED INTERACTION OF CO-ROTATING VORTICES"

Proceedings 3rd ONERA-DLR Aerospace Symposium (ODAS 2001), Paris, France, June 2001, pp. S2-3/1-10

The two- and three-dimensional interactions of a pair of co-rotating vortices, representing a simplified model of flows found in the extended near wake behind aircraft wings, are analyzed using water tank experiments and numerical simulations. At low Reynolds numbers (Re), the vortices undergo two-dimensional merging, when the core size exceeds a certain fraction of the vortex separation distance. The time it takes to reach this limit increases with Re . At higher Re , a three-dimensional instability is observed, showing the characteristics of an elliptic instability of the vortex cores. The spatial structure of the amplified unstable modes, as well as their growth rate as function of axial wavelength are given and compared to theoretical predictions, showing excellent agreement between the three approaches.

The instability is found to rapidly generate small-scale motion, initiating merging for smaller core sizes and producing a turbulent final vortex.

Leweke, T., Thompson, M. C. and Hourigan, K.

"VORTEX DYNAMICS ASSOCIATED WITH THE COLLISION OF A SPHERE WITH A WALL"

Physics of Fluids, Vol. 16, No. 9, September 2004, pp. L74-L77

For moderate Reynolds numbers, a sphere striking a wall in the normal direction leads to the trailing recirculating wake threading over the sphere and developing into a complex vortex ring system as it interacts with the wall. The primary vortex ring, which consists of vorticity from the wake, persists and convects slowly outwards away from the sphere due to the motion induced from its image. The structure and evolution of this vortex system is quantified through a combined experimental and numerical study. At higher Reynolds numbers a non-axisymmetric instability develops, which leads to rapid dispersion of the ring system. A comparison of the wavelength and growth rate, predicted from both linear stability theory and direct simulations, with idealized models indicates that the mechanism is dominated by a centrifugal instability at the edge of the primary vortex core.

Lewellen, D. C. and Lewellen, W. S.

"ROLE OF TURBULENCE IN CHEMICAL AND DYNAMICAL PROCESSES IN THE NEAR-FIELD WAKE OF SUBSONIC AIRCRAFT; FINAL REPORT"

USGRDR0216, West Virginia University, March 2002, Morgantown, WV

During this grant, covering the period from September 1998 to December 2001, we continued the investigation of the role of turbulent mixing in the wake of subsonic aircraft initiated in 1994 for NASA's Atmospheric Effects of Aviation Project. The goal of the research has been to provide sufficient understanding and quantitative analytical capability to assess the dynamical, chemical, and microphysical interactions in the near-field wake that have the greatest potential to influence the global atmospheric impact of the projected fleet of subsonic aircraft. Through large-eddy simulations we have shown that turbulence in the early wake dynamics can have a strong effect on both the ice microphysics of contrail evolution and on wake chemistry. The wake vortex dynamics are the primary determinant of the vertical extent of the contrail; this together with the local wind shear largely determines the horizontal extent. The fraction of the initial ice crystals surviving the wake vortex dynamics, their spatial distribution, and the ice mass distribution are all sensitive to the aircraft type, assumed initial ice crystal number, and ambient humidity and turbulence conditions. Our model indicates that there is a significant range of conditions for which a smaller aircraft such as a B737 produces as significant a persistent contrail as a larger aircraft such as a B747, even though the latter consumes almost five times as much fuel. Large-eddy simulations of the near wake of a B757 provided a fine-grained chemical-dynamical representation of simplified NO_x - HO_x chemistry in wakes of ages from a few seconds to several minutes. By sampling the simulated data in a manner like that of in situ aircraft measurements it was possible to provide a likely explanation for a puzzle uncovered in the 1996

SUCCESS flight measurements of OH and HO₂. The results illustrate the importance of considering fluid dynamics effects in interpreting chemistry results when mixing rates and species fluctuations are large, and demonstrate the feasibility of using 3D unsteady LES with coupled chemistry to study such phenomena.

Lewellen, D. C. and Lewellen, W. S.

"THE EFFECTS OF AIRCRAFT WAKE DYNAMICS ON CONTRAIL DEVELOPMENT"

Journal of the Atmospheric Sciences, Vol. 58, No. 4, February 2001, pp. 390-406

Results of large-eddy simulations of the development of young persistent ice contrails are presented, concentrating on the interactions between the aircraft wake dynamics and the ice cloud evolution over ages from a few seconds to ~30 min. The 3D unsteady evolution of the dispersing engine exhausts, trailing vortex pair interaction and breakup, and subsequent Brunt-Vaisala oscillations of the older wake plume are modeled in detail in high-resolution simulations, coupled with a bulk microphysics model for the contrail ice development. The simulations confirm that the early wake dynamics can have a strong influence on the properties of persistent contrails even at late times. The vortex dynamics are the primary determinant of the vertical extent of the contrail (until precipitation becomes significant); and this together with the local wind shear largely determines the horizontal extent. The ice density, ice crystal number density, and a conserved exhaust tracer all develop and disperse in different fashions from each other. The total ice crystal number can be significantly reduced due to adiabatic compression resulting from the downward motion of the vortex system, even for ambient conditions that are substantially supersaturated with respect to ice. The fraction of the initial ice crystals surviving, their spatial distribution, and the ice mass distribution are all sensitive to the aircraft-type, ambient humidity, assumed initial ice crystal number, and ambient turbulence conditions. There is a significant range of conditions for which a smaller transport such as a B737 produces as significant a persistent contrail as a larger transport such as a B747, even though the latter consumes almost five times as much fuel. The difficulties involved in trying to minimize persistent contrail production are discussed.

Lewellen, D. C. and Lewellen, W. S.

"LARGE-EDDY SIMULATIONS OF THE VORTEX-PAIR BREAKUP IN AIRCRAFT WAKES"

AIAA Journal, Vol. 34, No. 11, November 1996, pp. 2337-2345.

We have utilized large-eddy simulations to simulate the transition from an aircraft wake dominated by the interaction of vortex-pair dynamics and engine plume buoyancy to one dominated by atmospheric dispersion. Our investigation concentrates on the period from a few seconds to several minutes after the wake is generated, during which the essentially two-dimensional vortex-pair is broken up into a variety of three-dimensional eddies. Our initial conditions are taken from near-wake simulations for three aircraft, the B-737, the B-747, and the ER-2. Comparisons of our simulations, for conditions representatives of the atmosphere in the upper troposphere and the lower stratosphere, with wake

photographs taken from the ground show very similar features. In the absence of wind shear, the vortex pair go through a linking instability that is affected both by engine buoyancy and ambient turbulence. The resultant series of vortex rings continue to descend, leaving the wake with the appearance of a series of suspended puffs. When the mean atmospheric shear is sufficiently large, the ambient vorticity can erode one member of the vortex pair, leading to a breakup mode with a much shorter wavelength.

Lewellen, D. C. and Lewellen, W. S.

"EFFECTS OF AIRCRAFT WAKE DYNAMICS ON MEASURED AND SIMULATED NO_x AND HO_x WAKE CHEMISTRY"

Journal of Geophysical Research, Vol. 106, No. D21, November 2001, pp. 27,661-27,672.

High-resolution numerical large-eddy simulations of the near wake of a B757 including simplified NO_x and HO_x chemistry were performed to explore the effects of dynamics on chemistry in wakes of ages from a few seconds to several minutes. Dilution plays an important basic role in the NO_x - O₃ chemistry in the wake, while a more interesting interaction between the chemistry and dynamics occurs for the HO_x species. These simulation results are compared with published measurements of OH and HO₂ within a B757 wake under cruise conditions in the upper troposphere taken during the Subsonic Aircraft Contrail and Cloud Effects Special Survey (SUCCESS) mission in May 1996. The simulation provides a much finer grained representation of the chemistry and dynamics of the early wake than is possible from the 1 s samples taken in situ. The comparison suggests that the previously reported discrepancy of up to a factor of 20 - 50 between the SUCCESS measurements of the [HO₂]/[OH] ratio and that predicted by simplified theoretical computations is due to the combined effects of large mixing rates around the wake plume edges and averaging over volumes containing large species fluctuations. The results demonstrate the feasibility of using three-dimensional unsteady large-eddy simulations with coupled chemistry to study such phenomena.

Lewellen, D. C., Lewellen, W. S., Poole, L. R., DeCoursey, R. J., Hansen, G. M., Hostetler, C. A. and Kent, G. S.

"LARGE-EDDY SIMULATIONS AND LIDAR MEASUREMENTS OF VORTEX-PAIR BREAKUP IN AIRCRAFT WAKES"

AIAA Journal, Vol. 36, No. 8, August 1998, pp. 1439-1445

Results of large-eddy simulations of an aircraft wake are compared with results from ground-based lidar measurements made at NASA Langley Research Center during the Subsonic Assessment Near-Field Interaction Flight Experiment field tests. Brief reviews of the design of the field test for obtaining the evolution of wake dispersion behind a Boeing 737 and of the model developed for simulating such wakes are given. Both the measurements and the simulations concentrate on the period from a few seconds to a few minutes after the wake is generated, during which the essentially two-dimensional vortex pair is broken up into a variety of three-dimensional eddies. The model and experiment show

similar distinctive breakup eddies induced by the mutual interactions of the vortices, after perturbation by the atmospheric motions.

Lewellen, W. S.

"A SOLUTION FOR THREE-DIMENSIONAL VORTEX FLOWS WITH STRONG CIRCULATION"

J. Fluid Mech., Vol. 14, Part 3, November 1962, pp. 420-432

The Navier-Stokes equations for a viscous, incompressible fluid is considered for a steady, axisymmetric flow composed of a strong rotation combined with radial sink flow which exhausts axially inside a finite radius. The equations are reduced to two coupled partial differential equations in terms of the stream function and circulation.

Lewis, B., Bone, R. S., Mendolia, A. S. and Nguyen, Q. A.

"PILOT CONDUCT OF A RELATIVE SPACING TASK DURING CLOSELY SPACED PARALLEL RUNWAY OPERATIONS"

Report MTR190106, March 2019, Mitre Corporation, McLean, VA.

This is a MITRE report entitled 'Pilot Conduct of a Relative Spacing Task during Closely Spaced Parallel Runway Operations -- Interval Management Paired Approach Human-in-the-Loop Simulation Report.' The report documents a HITL simulation to evaluate flight crew acceptability of IM PA operations, procedures, and display elements during nominal and off-nominal operations.

Lewis, M. S., Meserole, J. S., Dunn, M. J. and Tillotson, B. J.

"SYSTEMS AND METHODS FOR TRACING AIRCRAFT VORTICES"

US Patent 8,376,284 B2, February 2013.

Systems and methods for tracing aircraft vortices. One method includes directing a tracer from a first aircraft into a vortical flow generated by the first aircraft. The method can further include detecting a characteristic corresponding to the presence of the tracer directed into the vortical flow. Based at least in part on the detected characteristic, the method can include directing the flight of the first aircraft, or a second aircraft following the first, or both.

Lewis, M. S., Meserole, J. S., Dunn, M. J. and Tillotson, B. J.

"SYSTEMS AND METHODS FOR TRACING AIRCRAFT VORTICES"

US Patent 7,874,522 B2, January 2011.

Systems and methods for tracing aircraft vortices. One method includes directing a tracer from a first aircraft into a vortical flow generated by the first aircraft. The method can further include detecting a characteristic corresponding to the presence of the tracer directed into the vortical flow. Based at least in part on the detected characteristic, the method can include directing the flight of the first aircraft, or a second aircraft following the first, or both.

Lewis, T. A.

"FLIGHT DATA ANALYSIS AND SIMULATION OF WIND EFFECTS DURING AERIAL REFUELING"

MS Thesis, May 2008, University of Texas, Arlington, TX.

This thesis presents an analysis of data obtained in an automated aerial refueling test flight with a KC-135 as the tanker and a Learjet 25 as the surrogate receiver unmanned aerial vehicle (UAV). The purpose is to identify the wind induced by the tanker wake and its effect on the receiver aircraft. From the available flight data, a direct computation of the winds experienced by the tanker and receiver is carried out. The mean variation of the receiver wind is compared with the tanker wind when the receiver is at the observation and contact positions. This results in the identification of the wake-induced wind. A spectrum analysis is conducted to characterize the turbulence and to identify the pilot effects. The thesis also presents methods used to model (i) prevailing wind, (ii) wake vortex induced wind and (iii) turbulence as the three sources of wind that the aircraft are exposed to and the approach used for incorporating the wind effect into the dynamic simulation of the aircraft. The test flight is simulated in various cases with different turbulence models and flight controllers. The simulation results are analyzed and compared with the flight data in terms of the power spectral densities and mean variations to validate the wind and turbulence modeling techniques.

Lezius, D. K.

"WATER TANK STUDY OF THE DECAY OF TRAILING VORTICES"

AIAA Journal, Vol. 12, No. 8, August 1974, pp. 1065-1071

Underwater towing experiments were carried out with a rectangular airfoil of aspect ratio 5.3 at 4 degree and 8 degree angles of attack and at chord-based Reynolds numbers between 2.2×10^5 and 7.5×10^5 . Tangential velocity measurements in the downstream region between 100 and 1000 chord lengths indicate rates of vortex decay proportional to $t^{-7/8}$ at 8 degrees, whereas previous flight tests show that the decay rate approaches $t^{-1/2}$ far downstream. The observed behavior is explained in terms of an analytical solution that includes time dependence of the turbulent eddy viscosity, $\sim \nu_m$. It shows that, for $m > 0$, an isolated turbulent vortex decays faster than $t^{-1/2}$. In this case, the decay is accompanied by increasing turbulent eddy viscosity, or levels of turbulence, which corresponds to turbulent nonequilibrium flow. The special case of vortex decay with equilibrium flow ($m=0$) leads to the well-known decay rate $t^{-1/2}$. Since, in towing tank experiments at low Reynolds number, turbulent vortex decay may occur predominantly in non-equilibrium, it is doubtful that such tests correctly

predict the late stage of decay of aircraft trailing vortices, when turbulence is the only dissipating mechanism.

Lezius, D. K.

"ANALYTICAL SOLUTION FOR INVISCID VORTEX ROLLUP FROM ELLIPTICALLY LOADED WINGS"

Journal of Aircraft, Vol. 12, No. 11, November 1975, pp. 911-914

An explicit analytical perturbation solution is presented that is based upon the Betz rollup theory for the vortex circulation after rollup from wings with elliptically distributed span loading. Since the resulting series solution converges rapidly, accurate and uniformly valid results emerge for the complete rollup when only the first three terms of the expansion are retained.

Lezius, D. K.

"UNSTABLE WING VORTEX ROLLUP INDUCED BY LIFT TAILORING IN THE WING-TIP REGION"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 23-1 - 23-10

The effects of modifying the circulation distributions near the tips of lifting wings on the stability of vortex rollup are investigated. Analytical considerations indicate that maintaining a positive spanwise lift gradient near and at the wing tips should result in unstable rollup of the vorticity originating in the region of increased wing-tip lift loading. The instability of the rollup is predicted by the Rayleigh stability criterion for rotating fluids and results from the attempted rollup of the wing vorticity in the tip region into a circular flow with radially decreasing circulation. Preliminary experiments with a rectangular wing with lift loading increasing toward the tip have demonstrated that rollup is prevented by turbulent rotating motions that are generated in the unstable arrangement of vorticity layers. The resulting turbulent vortex wake presents the appearance of one usually observed at large distances downstream of the wing.

Li, C., Dong, H. and Cheng, B.

"EFFECTS OF ASPECT RATIO AND ANGLE OF ATTACK ON TIP VORTEX STRUCTURES AND AERODYNAMIC PERFORMANCE FOR ROTATING FLAT PLATES"

AIAA Paper 2017-3645, June 2017, Denver, CO.

Numerical simulations are used to investigate the effects of aspect ratio and angle of attack on the vortex structure, circulation, and aerodynamic performance of revolving wings at a low Reynolds number regime (200 ~ 1600). Rectangular wings with various aspect ratio (1 ~ 8) are considered and rotating from rest at angle of attack ranging from 15 to 90 degrees. Simulations are carried out using

an in-house immersed-boundary-method-based direct numerical simulation (DNS) solver. A detailed analysis of the vortex formation shows that the general wake pattern near the wingtip shift from a single vortex loop to a pair of counter-rotating vortex loops. This tip vortex evolution was found related to the strength of LEV. In general, the stronger LEV will enhance the counter-pair trailing-edge vorticity. As the TEV increased, a secondary tip vortex will be formed at the bottom corner of wingtip and generate a pair of counter-rotating tip vortex loops. With the increment of the Reynolds number, these vortex loops will interact with each other and form hairpin-like vortical structures in the tail of the arc-shaped vortex loops. In addition to the vortex structures, the aerodynamic loading and power consumption were also examined. The findings from this work could be used to further understand the vortex dynamics of finite-aspect-ratio revolving wings at high angle of attack.

Li, D., and Wang, H.

"WAKE VORTEX EFFECT MODELING AND SIMULATION IN AUTOMATED AERIAL REFUELING"

Journal of Beijing University of Aeronautics and Astronautics, Vol. 36, No. 7, July 2010, pp. 776-780.

According to the request of automated aerial refueling, the formation and distribution of wake vortex behind a large aerial tanker was discussed. A modified horseshoe vortex model that includes the effect of vortex descent and diffusion over time was given. This model was linearized nearby the mass point of the receiver and an averaging technique was implemented to compute effective wind on the receiver. The effective wind components and gradients were introduced into the nonlinear aircraft equations through aerodynamic equivalent to determine the effect on the receiver's dynamics. Computer simulation of receiver/wake vortex encounters in aerial refueling was built by Matlab/Simulink. The results show that the wake vortex model can exactly describe the interference between the receiver and the tanker. This behavior is well matched with the feeling of the receiver's pilot. This model can also be used for the flight safety about large aircraft during taking off and interaction analysis in tight formation flight. [In Chinese.]

Li, D., Luo, K. and Fan, J.

"BUOYANCY EFFECTS IN AN UNSTEADY STRATIFIED TURBULENT BOUNDARY LAYER FLOW"

Physics of Fluids, Vol. 29, 2017, pp. 015104-1 to 015104-17.

Direct numerical simulation has been performed to investigate the effect of buoyancy on an unstably stratified turbulent boundary layer with the Oberbeck-Boussinesq approximation. The simulation results show that the mean values of the streamwise velocity and scalar fields are increased in the near-wall region but decreased in the outer layer under the effect of buoyancy, which leads to significant increases in the skin-friction drag and heat transfer. In addition, it is found that the unstable thermal stratification results in large increases in the intensities of the near-wall streamwise vortices and high- and low-speed streaks, and a reduction in the mean diameter of the vortical structures. Moreover, the turbulent coherent structures become less organized due to the stratification effect.

With respect to the neutral boundary layer flow, the outer vortical structures tend to bias the direction of the principal extensional strain towards the vertical plane in the unstably stratified flow.

Li, H., Burggraf, O. R. and Conlisk, A. T.

"FORMATION OF A ROTOR TIP VORTEX"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 739-749

The origin of the tip vortex is described and important properties, such as core radius and circulation, as a function of these parameters, are calculated. Even though a large amount of computational and experimental work on the rotor wake has been published, little of a quantitative nature is known about the origin of the main component of the rotor wake, the tip vortex, as a function of the rotor speed, rotor blade geometry, and angle of attack. Experimental data by several workers have revealed little dependence on the Reynolds number. This lack of dependence on Reynolds number will hold only if the flow remains substantially unseparated, although it may be noted that drag coefficients of bluff bodies are remarkably constant over a wide range of Reynolds number. The rotor blade is assumed to be of large aspect ratio, that is, to leading order in the blade aspect ratio, it appears infinite in length. In this limit case, the analytical solution for the bound circulation on a fixed wing is shown to be extendable to the rotary wing case when the blade is viewed as a lifting line. Lifting-surface results are obtained also, and these compare with the lifting-line results for the bound circulation.

Li, H., Burggraf, O. R. and Conlisk, A. T.

"ON THE FORMATION OF A TIP-VORTEX"

AIAA Paper No. 2000-0282, Reno, NV, January 2000

The helicopter-rotor wake is among the most complex flowfields in aerodynamics. Even though a large amount of computational and experimental work on the rotor wake has been published, little of a quantitative nature is known about the origin of the main component of the rotor wake, the tip-vortex, as a function of the rotor speed, rotor blade geometry, and angle of attack. The objective of this paper is to investigate whether classical inviscid lifting surface methods applied locally near the wing tip can describe the origin of the tip vortex. Correlation of experimental data by several workers has revealed little dependence on the Reynolds number. Of course, this lack of dependence on Reynolds number will hold only if the flow remains substantially unseparated, though it may be noted that drag coefficients of bluff bodies are remarkably constant over a wide range of Reynolds number. The rotor blade is assumed to be of large aspect ratio and the method of Matched Asymptotic Expansions is used to calculate the bound circulation near the wing tip. The primary objective of this work is to predict the formation of the rotor tip vortex as a function of physical parameters such as angle of attack, rotor speed, and blade aspect ratio. While the rotor-blade tip-vortex is of primary interest here, the techniques developed are applied first to the simple problem of the aircraft wing. Results for the bound circulation on a rotary wing are presented subsequently.

Li, H., Conlisk, A. T. and Burggraf, O. R.

"THE FORMATION OF ROTOR TIP-VORTICES"

53rd Annual Meeting of the Division of Fluid Dynamics, American Physical Society, November 2000, Washington, DC.

The helicopter rotor wake is composed of a strong tip-vortex and the relatively weak inboard sheet and the tip-vortex is the dominant component. The objective of this paper is to investigate whether classical inviscid lifting-line and lifting-surface methods applied locally near the rotor-tip can describe the origin of the tip-vortex. The rotor blade is assumed to be of large aspect ratio and the computations for the bound circulation are modeled on the method of matched asymptotic expansions. It is shown that in the tip region, an analytical solution for the bound circulation on the rotary wing may be obtained based on lifting-line theory whose form is like that of the fixed wing which is given by Stewartson except that there is an additional parameter which is dependent on the angle of attack, the aspect ratio and the number of blades. The formation of the rotor tip-vortex has been computed also. It is shown that the tip-vortex does not roll up completely at the trailing edge of the rotor blade as assumed in many rotor wake models; instead, the circulation of the tip-vortex develops downstream and approaches a constant asymptotically. The experiments on the rotor near wake show that the wake geometry is not a perfect helix. Two types of wake models (vortex-cylinder and discrete vortex-ring model) are used to consider the influence of rotor-wake contraction and the numerical results compare well with experimental data.

Li, J., Gao, H., Li, Y., Wang, X. and Chandrasekar, V.

"CIRCULATION RETRIEVAL OF SIMULATED WAKE VORTICES UNDER RAINY CONDITION WITH A SIDE-LOOKING SCANNING RADAR"

IEEE Transactions on Aerospace and Electronic Systems, Vol. 54, No. 2, April 2018, pp. 569-584.

The strength of a wake vortex can be well described by vortex circulation. In the area of aviation safety, it serves as a crucial parameter for assessing hazards caused by wake vortices, and its retrieval has attracted much attention in the past decades. Generally, radar is a very promising detection sensor for wake vortices generated under rainy condition where the scattering is mainly caused by the raindrops driven by wake vortices. This makes it possible to retrieve the circulation of wake vortices by sensing and quantifying the motion of these raindrops. This paper proposes the use of a side-looking radar, whose beam scans up and down alternately, for detecting wake vortices. In this method, raindrops that make major contribution to the total scattering are identified as characteristic-size raindrops, and their motion equation is established to connect their motion to the dynamics of wake vortices. When the velocity and acceleration of characteristic-size raindrops are well estimated from the Doppler spectra, the motion equation can be well solved by the nonlinear least squares method to yield the target parameter, circulation. At the same time, two other important parameters (vortex spacing and vortex-core height) can be retrieved as well. Numerical simulation results verify good performance of the retrieval method.

Li, J., Wang, T. and Wang, X.

"RADAR SCATTERING ANALYSIS OF WAKE VORTEX UNDER DIFFERENT WEATHER CONDITIONS"

2016 Progress in Electromagnet Research Symposium (PIERS), August 2016, Shanghai, China.

Wake vortex is a kind of largely-scaled distributed complex objects, and its radar scattering characteristics are very difficult to analysis. Generally, wake vortex can be classified into two categories in terms of weather conditions: clear air condition and precipitation condition (fog, rain, snow). Different wake vortices have different scattering mechanisms and characteristics. This paper presents some preliminary research results of wake vortex scattering, and some scattering mechanisms are briefly depicted.

Li, J., Wang, T., Qu, L., Wang, H. and Wang, X.

"CIRCULATION RETRIEVAL OF WAKE VORTEX IN FOG WITH AN UPWARD-LOOKING MONOSTATIC RADAR"

IEEE Transactions on Aerospace and Electronic Systems, Vol. 52, No. 1, February 2016, pp. 169-180.

Detection and parameter retrieval of aircraft wake vortices have attracted much attention in air traffic management and related fields. In foggy weather conditions, the scattering of a wake vortex is mainly determined by the fog drops carried by the velocity field of the wake. By taking the fog drops' property of weak inertia into account, a new theoretical method to retrieve the circulation of a wake vortex generated in fog is proposed in this paper. In the method, an upward-looking monostatic radar is employed to obtain the Doppler velocities of radar cells along the symmetric line of the wake vortex, and then the circulation can be obtained through a very simple expression with respect to the Doppler velocities and the length of the radar cells. Numerical simulation results verify the good performance of the method.

Li, J., Wang, X. and Wang, T.

"RAPID MODELING OF DISTRIBUTION OF AIRCRAFT WAKE DIELECTRIC CONSTANT BASED ON HORSE-SHOE VORTEX MODEL"

Acta Aeronautica et Astronautica Sinica, Vol. 30, No. 7, July 2009, pp. 1214-1218.

For the convenience of the study of aircraft wake vortex scattering characteristics, a rapid modeling method for the wake dielectric constant distribution is put forward. In this article, the induced velocity field of an aircraft wake is obtained based on the horse-shoe vortex model. From the velocity field, the Euler equation and isentropic flow method are used to work out the thermodynamic parameter distribution of the wake vortex, and then the dielectric constant distribution is obtained. At the same time, a method to extrapolate the result from one wake to another is proposed to avoid duplicate computation. This method has the advantage of requiring less computation with few parameters. Therefore, it is a rapid and efficient method to simulate the aircraft wake dielectric constant distribution. [In Chinese.]

Li, J., Wang, X. and Wang, T.

"SCATTERING MECHANISM OF AIRCRAFT WAKE VORTICES GENERATED IN CLEAR AIR"

IEEE Radar Conference, May 2010, Washington, DC, pp. 117-122.

To provide help to the development of radar detection technology on wake vortices, the scattering mechanism of a wake vortex is studied. The dielectric constant of wake vortices is divided into two terms regarding the density variation and water vapor variation, respectively. The effects of these two variations on the RCS of wake vortices are investigated to find the scattering mechanism. Research findings show that in the low frequency band, the density variation is the dominant factor to the total RCS of wake vortex; while in the frequency band, the dominant factor turns out to be the water vapor variation.

Li, J., Wang, X. and Wang, T.

"MODELING THE DIELECTRIC CONSTANT DISTRIBUTION OF WAKE VORTICES"

IEEE Transactions on Aerospace and Electronic Systems, Vol. 47, No. 2, April 2011, pp. 820-831.

The study of scattering characteristics of a wake vortex is very important for hazard avoidance, especially near airports. Obtaining the dielectric constant distribution is one of the basic issues in the scattering study for radar detection. The present work proposes a modeling method for the dielectric constant distribution. In the method the dielectric constant variation (also the radar cross section) due to the density variation and water vapor variation are studied. Research findings show that the density variation and water vapor variation serve as dominant factors to the radar cross section of a wake vortex in low frequency band and high frequency band, respectively.

Li, J., Wang, X., Wang, T. and Liu, Z.

"STUDY ON THE SCATTERING CHARACTERISTICS OF STABLE-STAGE WAKE VORTICES"

Radar Conf. - Surveillance for a Safer World, Oct. 2009, Bordeaux, France, pp. 1-5.

The present paper decomposes the study of wake vortex's scattering characteristics into three key problems. Based on the study of these three problems in detail, we obtained the scattering characteristics of the wake vortex, which include the frequency characteristic of RCS, the radiation pattern, the relation between RCS and the detection range, and the time evolution characteristic of RCS. Research findings can provide supports for the development of radar detection technology on wake vortex.

Li, J., Wang, X., Wang, T., Li, J., Xiao, S. and Liu, Z.

"HIGH RANGE RESOLUTION PROFILE OF SIMULATED AIRCRAFT WAKE VORTICES"

IEEE Transactions on Aerospace and Electronic Systems, Vol. 48, No. 1, January 2012, pp. 116-129.

Knowledge of radar scattering characteristics is very important to the development of radar detection technology on aircraft wake vortices. In this paper, the high range resolution (HRR) profile of the wake vortex is investigated. The HRR profile is observed to have a particular structure, from which the wingspan of the aircraft can be easily identified. This characteristic could be very useful to identify the wake vortex from the ambient air. At the same time, the Bragg scattering, whose characteristic and applicability are further explored, is used to explain the mechanism of such HRR profiles.

Li, W.

"FLOW/ACOUSTICS MECHANISMS IN TWO- AND THREE-DIMENSIONAL WAKE VORTICES"

Ph.D. Thesis, 2007, Kansas State University, Manhattan, KS

In this study, a vortex particle method is used to simulate incompressible vortical flows, specifically aircraft wake vortices. This is particularly suitable for a wake vortex system that is slowly varying in the axial direction and has a high Reynolds number and low Mach number. The flow field, in the form of vorticity, is employed as the source in the far-field acoustic calculation using a vortex sound formula that enables computation of acoustic signals radiated from an approximated incompressible flow field. In a two-dimensional vortex system, the stretching effect in the axial direction is neglected. The purpose of this study is to focus on vortex core behaviors. A numerical simulation is performed in a more realistic wake consisting of a counter-rotating vortex pair with inviscid ground effects and shear flows. A Kirchhoff spinning-core vortex model is thus used as a starting point. In a vortex system with multiple vortices, such as complicated aircraft vortex wake vortices, the sound emission frequency of the unsteady vortex core is subjected to change because of interactions between multiple vortices. The behaviors of the influence, indicated by the ratio between the core size and the distance of the vortices, are investigated as well as the underlining vortex core dynamic mechanisms. Cases of co-rotating vortices and a multiple-vortex system composed of two counter-rotating vortex pairs are studied for applications to aircraft wake vortex sound.

Li, W., Zheng, Z. C. and Xu, Y.

"FLOW/ACOUSTIC MECHANISMS IN THREE-DIMENSIONAL VORTICES UNDERGOING SINUSOIDAL-WAVE INSTABILITIES"

Proceedings of the ASME International Mechanical Engineering Congress and Exposition, IMECE-2007-43163, November 2007, Seattle, Washington

It has been identified that vorticity in a vortex core directly relates to the frequency of a significant sound peak from an aircraft wake vortex pair where each of the vortices is modeled as an elliptic core Kirchhoff vortex. In three-dimensional vortices, sinusoidal instabilities at various length scales result in

significant flow structure changes in these vortices, and thus influence their radiated acoustic signals. In this study, a three-dimensional vortex particle method is used to simulate the incompressible vortical flow. The flow field, in the form of vorticity, is employed as the source in the far-field acoustic calculation using a vortex sound formula that enables computation of acoustic signals radiated from an approximated incompressible flow field. Cases of vortex rings and a pair of counter-rotating vortices are studied when they are undergoing both long- and short-wave instabilities. Both inviscid and viscous interactions are considered and effects of turbulence are simulated using sub-grid-scale models.

Li, X. and Jacob, J. D.

"INITIAL SPACING EFFECTS ON CO-ROTATING TIP VORTEX FORMATION AND MERGER"

AIAA Paper No. 2000-2219, Denver, CO, June 2000

Preliminary results are presented from a study on the evolution, interaction, and merger of multiple trailing vortices in a towing tank and wind tunnel. The current study is limited to two corotating (like-signed) vortices of nearly equal magnitude. Various configurations of symmetric semispan airfoils are used to generate the vortex pair. The initial separation distance of the vortices is varied to investigate the effect on merger characteristics. In the wind tunnel, a seven-hole probe is used to extract the 3D average velocity in the vortex wake. In the tow tank, a laser sheet illuminates tracer particles in the flow and a digital camera is used to capture a sequence of PIV images. Planar velocity and vorticity fields are derived from these images using an adaptive Lagrangian parcel tracking algorithm. Merger of the corotating vortex pairs is observed at all Reynolds numbers and separation distances for all tow tank experiments and for the wind tunnel experiments with small initial separation.

Liamshev, L. M., and Skvortsov, A. T.

"EMISSION OF SOUND BY LOCALIZED VORTICES IN A WEAKLY COMPRESSIBLE MEDIUM (REVIEW)"

Akusticheskii Zhurnal (ISSN 0320-7919), Vol. 34, Sept.-Oct. 1988, p. 769-790. [In Russian]

Results of recent theoretical studies of some of the most characteristic phenomena associated with sound emission by vortices are discussed with particular reference to localized vortices. The theoretical analysis is carried out for the simple case of a homogeneous isotropic fluid, facilitating the quantitative description of the principal physical characteristics of the excitation of acoustic oscillations by vortices. The general methods of analysis and specific examples presented here can be useful in obtaining rough estimates of similar effects in more complex hydrodynamic systems, such as the atmosphere, the ocean, plasma, and super fluids.

Liang, X. and Ramaprian, B. R.

"VISUALIZATION OF THE WING-TIP VORTEX IN TEMPORAL AND SPATIAL PRESSURE GRADIENTS"

Journal of Fluids Engineering, Vol. 113, September 1991, pp. 511-515.

The evolution of the longitudinal vortex in the near field of a rectangular wing has been visualized using smoke and laser light sheet. The smoke photographs have been used to obtain qualitative and some quantitative information on the effect of small temporal and spatial pressure gradients on the evolution of the vortex in this region. The experiments indicate that even small temporal retardation of the flow produce a significant increase in the vortex size. This effect becomes larger with increase in retardation, angle of incidence and distance downstream from the trailing edge. Also, vortex 'breakdown' was found to occur in many temporal-deceleration experiments. The vortex evolution was, however, found to be relatively insensitive to the presence of small spatial adverse pressure gradients along the flow direction. The study is preliminary in nature and needs to be supported by more extensive quantitative measurements.

Libby, J. C., Dasey, T. J. and Heinrichs, R. M.

"WAKE VORTEX AND HOVER DOWNWASH MEASUREMENTS OF THE V-22 AND XV-15 TILTROTOR AIRCRAFT"

Military Sensing Systems Active Electrooptic Systems Conf., Redstone Arsenal, Huntsville, AL, April 2001

Lincoln Laboratory, in coordination with Bell Helicopter Textron, has conducted measurements of the wake vortex and hover downwash characteristics of the V-22 and XV-15 tiltrotor aircraft. Vortices generated in different forward flight configurations were detected and tracked by our mobile continuous-wave coherent CO₂ laser radar. The same lidar system was used to rapidly acquire downwash velocity profiles from the hovering aircraft. This is the first time the wake of a tiltrotor aircraft has been measured using laser radar. It is also the first time that a laser radar system has been used to record hover downwash data. Measurements made in August 2000 at the Bell Helicopter Test Flight Facility in Arlington, Texas are presented here, along with an analysis of the vortex and hover data.

Liepmann, D., Marcus, P. S. and Savas, O.

"MITIGATION OF AIRCRAFT WAKE VORTICES"

UCB-ITS-RR-94-14, December 1994, Institute of Transportation Studies, University of California, Berkeley, CA

Airport capacity, hence the ground transportation around it is coupled to landing and take-off frequency of the aircraft. This frequency is determined by the longevity of the wake vortex pair. The research program is aimed at first understanding the issues determining the life span of the wake, then to destabilize it and hasten its demise to allow more aircraft in the queue. We have now completed velocity vector field measurements in the wake of rectangular wing. In this phase, we used rectangular planform of aspect ratio of 8 to study the behavior of a clean vortex wake. The wake system is extremely stable. The second phase will investigate the effect of broken symmetry on the longevity of the wake vortices. For this phase, a dynamic model will be constructed where there will be provisions

for modifying the vorticity distribution in the wake. These experiments will be guided by numerical studies which are concurrent.

Light, J. S.

"TIP VORTEX GEOMETRY OF A HOVERING HELICOPTER ROTOR IN GROUND EFFECT"

Journal of the American Helicopter Society, Vol. 38, April 1993, pp. 34-42.

The wide-field shadowgraph method has been used to photograph the tip vortices of a hovering helicopter rotor in ground effects. The shadowgraphs were used to obtain quantitative measurements of the rotor tip vortex geometry both in and out of ground effect. Many important phenomena are visible in the rotor wake using this method. These include the variation in descent and contraction rates of the tip vortices in ground effect, and the interaction between tip vortices in the far wake. The tip vortex geometry from the shadowgraphs is compared with the tip vortex geometry predicted using a free wake hover performance analysis. The free wake analysis accurately predicts the tip vortex geometry both in and out of ground effect. Performance data from the test is compared with the performance predicted using several methods, including the free wake analysis. All methods provided reasonable predictions of the helicopter performance in ground effect.

Light, J. S.

"TIP VORTEX GEOMETRY OF A HOVERING HELICOPTER ROTOR IN GROUND EFFECT"

45th Annual Forum of the American Helicopter Society, May 1989, Boston, MA.

The wide-field shadowgraph method has been used to photograph the tip vortices of a hovering helicopter rotor in ground effects. The shadowgraphs were used to obtain quantitative measurements of the rotor tip vortex geometry both in and out of ground effect. Many important phenomena are visible in the rotor wake using this method. These include the variation in descent and contraction rates of the tip vortices in ground effect, and the interaction between tip vortices in the far wake. The tip vortex geometry from the shadowgraphs is compared with the tip vortex geometry predicted using a free wake hover performance analysis. The free wake analysis accurately predicts the tip vortex geometry both in and out of ground effect. Performance data from the test is compared with the performance predicted using several methods, including the free wake analysis. All methods provided reasonable predictions of the helicopter performance in ground effect.

Light, J. S. and Felker, F. F.

"ANALYSIS OF INDUCED VELOCITIES IN THE WAKE OF A HOVERING HELICOPTER ROTOR"

AIAA Paper 1987-2283, Monterey, CA, August 1987

A simple analytical method has been developed to predict the induced velocities at the tip vortex in the wake of a hovering helicopter rotor. The wake model in the analysis includes the blade bound

vortex as well as a tip vortex and vortex sheet trailed from each blade. Standard, prescribed wake models were used to describe the geometry of the tip vortex and the vortex sheet. Curved vortex elements were used to model the tip vortices and the vortex sheets. The analysis was used to study the contribution from each wake component to the axial-induced velocity of the tip vortex. Results show a highly variable induced velocity at the tip vortex both before and after the first blade passage. However, the prescribed tip vortex models require a constant axial velocity of the tip vortex. This inconsistency between the prescribed axial velocity of the tip vortex and the velocity that the wake geometry induces on the tip vortex points to a limitation of the current prescribed tip vortex geometry models.

Lignarolo, L. E. M., Mehta, D., Stevens, R. J. A. M., Yilmaz, A. E., van Kuik, G., Andersen, S. J., Meneveau, C., Ferreira, C. J., Ragni, D., Meyers, J., van Bussel, G. J. W. and Holierhoek, J.

"VALIDATION OF FOUR LES AND A VORTEX MODEL AGAINST STEREO-PIV MEASUREMENTS IN THE NEAR WAKE OF AN ACTUATOR DISC AND A WIND TURBINE"

Renewable Energy, Vol. 94, 2016, pp. 510-523.

In this paper we report the results of a workshop organized by the Delft University of Technology in 2014, aiming at the comparison between different state-of-the-art numerical models for the simulation of wind turbine wakes. The chosen benchmark case is a wind tunnel measurement, where stereoscopic Particle Image Velocimetry was employed to obtain the velocity field and turbulence statistics in the near wake of a two-bladed wind turbine model and of a porous disc, which mimics the numerical actuator used in the simulations. Researchers have been invited to simulate the experimental case based on the disc drag coefficient and the inflow characteristics. Four large eddy simulation (LES) codes from different institutions and a vortex model are part of the comparison. The purpose of this benchmark is to validate the numerical predictions of the flow field statistics in the near wake of an actuator disc, a case that is highly relevant for full wind farm applications. The comparison has shown that, despite its extreme simplicity, the vortex model can reproduce the wake expansion and the centerline velocity with very high accuracy. Also, all tested LES models can predict the velocity deficit in the very near wake well, contrary to what was expected from previous literature. However, the resolved velocity fluctuations in the LES are below the experimentally measured values.

Lignarolo, L. E. M., Ragni, D., Ferreira, C. J. S. and van Bussel, G. J. W.

"EXPERIMENTAL QUANTIFICATION OF THE ENTRAINMENT OF KINETIC ENERGY AND PRODUCTION OF TURBULENCE IN THE WAKE OF A WIND TURBINE WITH PARTICLE IMAGE VELOCIMETRY"

AIAA Paper 2014-0706, January 2014, National Harbor, MD.

The rule of the tip-vortex pairwise instability ('leapfrogging') is investigated in relation to the process of kinetic energy transport and turbulence production within the shear layer of a horizontal-axis wind-turbine wake. Experiments are conducted in an open-jet wind-tunnel on a wind turbine model. Stereoscopic particle image velocimetry is employed to obtain the velocity field in a meridian plane encompassing a large portion of the wake past the rotor model. Measurements with both phase-

locked and unconditioned sampling techniques allow for a triple decomposition of the flow fields. The levels of turbulence intensity show a dominant role of random fluctuations after the location of the pairwise instability. Computation of the kinetic energy fluxes across the wake shear layer shows the presence of three main zones. Prior to the onset of the instability, vortices shed from the blade inhibit the turbulent mixing of the wake during its expansion. The region affected by leapfrogging exhibits a sudden increase of the net entrainment of kinetic energy. Downstream, the energy exchange is characterized by a pronounced turbulent mixing, only due to random turbulent motions. Leapfrogging determines the end of the wake expansion and with the onset of a more pronounced turbulent mixing, coincident with the beginning of the wake re-energizing process.

Ligneul, P. and Latorre, R.

"STUDY OF NUCLEI DISTRIBUTION AND VORTEX DIFFUSION INFLUENCE ON NUCLEI CAPTURE BY A TIP VORTEX AND NUCLEI CAPTURE NOISE"

Transactions of the ASME, Vol. 115, Sept. 1993, pp. 504-507.

Earlier studies of cavitation nuclei behavior in the presence of a Rankine tip vortex have shown that the nuclei are attracted or captured by the vortex pressure field and during this process noise is produced by the rapid growth. The present paper extends the study of Ligneul and Latorre (1989). The capture of nuclei by the tip vortex was characterized by an index M which depends on the nuclei radius, initial location, and the vortex circulation. To clarify the nuclei distribution effected by this capture process, the frequency of nuclei capture is derived in terms of the nuclei distribution $N(R)$. The influence of the tip vortex axial diffusion on the nuclei capture process is formulated and number results presented to show how vortex diffusion delays the nuclei capture. The paper closes with a discussion of the numerical simulation of the nuclei capture and noise generation by the tip vortex.

Likhachev, O. A.

"EQUILIBRIUM STATE OF TRAILING VORTICES: TWO-DIMENSIONAL MODEL OF A FAR-FIELD VORTEX WAKE"

Aerospace Science and Technology, Vol. 5, July 2001, pp. 329-338

The equilibrium statistical mechanics of a system composed of a large number of two-dimensional point vortices is employed to describe the vortex system shed from aircraft wings. According to this theory, these higher energy states of the vortex system can only be achieved by segregating the point vortices of like kind into two clusters that descend with a constant velocity. The solution is given in terms of the integral constraints for each cluster: total circulation, center of inertia, and kinetic energy. The negative non-dimensional inverse temperature of the system and the length scale related to angular momentum of a single trailing vortex are obtained versus initial interaction energy of the vortex system. Comparison of the theoretical results with available experimental data shows good agreement between the calculated tangential velocity distribution in the trailing vortex and the data.

The flow characteristics for three different wing loads are also compared to emphasize the effect of initial circulation distribution along a lifting wing on the vorticity distribution in the equilibrium trailing vortices.

Lim, C. C.

"RECENT ADVANCES IN 2D AND 2.5D VORTEX STATISTICS AND DYNAMICS"

AIAA Paper No. 2005-5158, Toronto, Canada, June 2005

This review paper offers both an overview of the recent developments in vortex statistics, and a detailed critical review of some of the advances as well as open problems in the area. A fruitful new direction in vortex dynamics concerns vortical systems with very large numbers of vortices in which statistical methods play a pivotal role. After a review of some of the older equilibrium statistical mechanics approaches, such as Onsager's Vortex gas theory, we survey the recent burst of interest and papers on the application of statistical mechanics to a wide range of problems. They include many interesting problems such as rotating stratified flows with natural applications to atmospheric and oceanic sciences. Special models that will be discussed include point vortex as well as vortex blob models in axisymmetric flows, in the plane, and in geophysical flows involving multi-layer baroclinic effects. A recent reverse application of a quantum path-integral Monte-Carlo algorithm to the Lions-Majda model for nearly parallel vortex filaments will be reviewed with numerical results. A connection between these statistical theories and the classical numerical method known as the vortex method will also be made. Many of these noteworthy advances are made possible by good Monte-Carlo algorithms, providing a cross-disciplinary aspect to the field. An important open problem in the field of the vortex gas is the exact partition function for any finite number of particles N and any finite temperature.

Lim, H.-B.

"NUMERICAL STUDY OF THE TRAILING VORTEX OF A WING WITH WING-TIP BLOWING"

PhD Thesis, March 1994, Stanford University, Stanford, CA.

Trailing vortices generated by lifting surfaces such as helicopter rotor blades, ship propellers, fixed wings, and canard control surfaces are known to be the source of noise, vibration, cavitation, degradation of performance, and other hazardous problems. Controlling these vortices is therefore of practical interest. The formation and behavior of the trailing vortices are studied in the present research. In addition, wing-tip blowing concepts employing axial blowing and spanwise blowing are studied to determine their effectiveness in controlling these vortices and their effects on the performance of the wing. The three-dimensional, unsteady, thin-layer compressible Navier-Stokes equations are solved using a time-accurate, implicit, finite difference scheme that employs LU-ADI factorization. The wing-tip blowing is simulated using the actuator plane concept, thereby not requiring resolution of the jet slot geometry. Furthermore, the solution blanking feature of the chimera scheme is used to simplify the parametric study procedure for the wing-tip blowing. Computed results

are shown to compare favorably with experimental measurements. It is found that axial wing-tip blowing, although delaying the rolling-up of the trailing vortices and the near-field behavior of the flowfield, does not dissipate the circulation strength of the trailing vortex farther downstream. Spanwise wing-tip blowing has the effect of displacing the trailing vortices outboard and upward. The increased 'wing-span' due to the spanwise wing-tip blowing has the effect of lift augmentation on the wing and the strengthening of the trailing vortices. Secondary trailing vortices are created at high spanwise wing-tip blowing intensities.

Lim, J. W. and Strawn, R. C.

"COMPUTATIONAL MODELING OF HART II BLADE-VORTEX INTERACTION LOADING AND WAKE SYSTEM"

J. Aircraft, Vol. 45, No. 3, May-June 2008, pp. 923-933

Correlations using a loosely coupled trim methodology of the CFD (OVERFLOW-2) and CSD (CAMRAD-II) codes are presented in order to calculate the helicopter rotor blade-vortex interaction (BVI) airloads and wake system for the HART II rotor at an advance ratio of 0.15. Five different grid models are studied in order to quantify the effects of grid refinement on rotor wake resolution. The fine grid model (fine near-body/fine off-body) has a total of 113 million grid points and it gives very good air loads predictions for the HART II baseline, minimum noise and minimum vibration cases. The rotor wake positions are also very well predicted by this fine grid model. The computed vorticity field for a young vortex using the fine grid model is compared with the measured PIV data and the results are surprisingly good. The fine grid model underpredicts the experimental value for maximum vorticity by only 29%. In addition, the predicted vortex core radius is 15% chord for the fine grid calculation while the measured data shows about 5% chord length. The predicted swirl velocity is, however, higher than the measured data for this vortex. The results in this paper provide the first quantitative comparisons of a measured flow field and CFD/CSD computed solutions for a helicopter rotor-wake system.

Lim, J. W. and van der Wall, B. G.

"AN ASSESSMENT OF 3-C PIV ANALYSIS METHODOLOGY FOR HART II MEASURED DATA"

NASA/TM-2010-216024 and TR-RDMR-AF-10-03, July 2010, US Army Research, Development and Engineering Command, Redstone Arsenal, AL.

Since the completion of the DNW test, HART II partners have put forth significant efforts to derive vortex properties from the measured data. These properties include vortex center, rotation angles of the vortex axis in the PIV measurement plane, maximum vorticity, core radius, and swirl velocity. Differences among the partners' results were found for some of these vortex properties, which required more effort to assess the physical significance of the differences. This was because the derived vortex properties were an integral of all the sub-processes in the complex PIV data analysis procedure, and more information was needed to resolve the differences in vortex properties. The objectives of this report are to discuss and summarize the parameters and techniques that could contribute to these

differences. The detailed comparisons in this report have helped establish a strong foundation for a PIV data analysis methodology in determining vortex properties.

Lim, J. W., Yu, Y. H. and Johnson, W.

"CALCULATION OF ROTOR BLADE-VORTEX INTERACTION AIRLOADS USING A MULTIPLE-TRAILER FREE-WAKE MODEL"

Journal of Aircraft, Vol. 40, No. 6, November-December 2003, pp. 1123-1130.

Analytical results of rotor blade-vortex interaction air loads are presented with two different wake models in the comprehensive analysis CAMRAD II, and these calculated results are compared with the experimental data obtained from the higher-harmonic-control aero acoustic rotor test (HART-I) program. The HART rotor was a 40 percent, Mach-scaled model of the hinge less BO-105 main rotor. Two wake models used in the comprehensive analysis are the single-trailer and the multiple-trailer free-wake models. The multiple-trailer wake model shows good prediction of lift distribution as a function of azimuth for baseline, minimum noise, and minimum vibration cases, and shows significant improvement relative to the single-trailer model in prediction of the tip vortex wake geometry.

Lim, T. T.

"AN EXPERIMENTAL STUDY OF A VORTEX RING INTERACTING WITH AN INCLINED WALL"

Experiments in Fluids, Vol. 7, 1989, pp. 453-463

An experimental study has been made on the interaction of a vortex ring with a plane solid boundary which is inclined to the axis of the ring. Dye visualizations of the ring during the interaction revealed (i) the formation of bi-helical vortex lines around the circumferential axis of the ring, and (ii) that these vortex lines were constantly being displaced along the circumferential axis on either side of the plane of symmetry and towards the region of the ring furthest away from the wall. Key factors which may be responsible for this phenomenon have been identified and are discussed in this paper.

Lim, T. T. and Cui, Y. D.

"ON THE GENERATION OF A SPIRAL-TYPE VORTEX BREAKDOWN IN AN ENCLOSED CYLINDRICAL CONTAINER"

Physics of Fluids, Vol. 17, April 2005, pp. 044105-1-044105-9

Earlier experimental studies [see H. U. Vogel, 'Experimentelle Ergebnisse uber die Laminare Stromung in einem zylindrischen Gehause mit darin roterender Scheibe' Max-Planck-Inst. Bericht 6 (1968) and M. P. Escudier, 'Observations of the flow produced in cylindrical container by a rotating endwall,' Exp. Fluids 2, 189 (1984)] showed that vortex breakdown in an enclosed cylindrical container with one rotating end wall could exhibit either one, two, or three recirculating bubbles depending on the combination of Reynolds number Re and aspect ratio H/R , at least for H/R less than 3.5. However, a

recent numerical study by Serre and Bontoux ['Vortex breakdown in a three-dimensional swirling flow,' J. Fluid Mech. 459, 347 (2002)] at $H/R = 4.0$ showed that under some conditions, an S-shape vortex structure follows by a spiral-type vortex breakdown could also be produced. This finding is most interesting because, to the best of our knowledge, a spiral-type vortex breakdown in an enclosed cylindrical container has not been produced previously in experiments. The aim of the present investigation is to verify if these vortex structures can be produced under laboratory conditions. Experiments conducted using dye visualization techniques confirm their existence, even for H/R as low as 3.65. However, attempts to produce similar vortex structures in low aspect ratio cases (H/R less than 2.5) by 'artificially' introducing three dimensionality into the flow was less successful. Here, the confined environment makes a bubble-type vortex breakdown extremely robust, and the imposed asymmetry merely distorts the bubble geometry. The present study also reveals that the formation of a bubble-type vortex breakdown is associated with helical instability of decreasing wavelength, and the S-shape structure is linked with a similar instability of increasing wavelength.

Lim, TT., Nickels, T. B. and Chong, M. S.

"A NOTE ON THE CAUSE OF REBOUND IN THE HEAD-ON COLLISION OF A VORTEX RING WITH A WALL"

Experiments in Fluids, Vol. 12, 1991, pp. 41-48

It is well documented that a trailing vortex pair approaching the ground, and a vortex ring colliding head-on with a rigid plane, experience a reversal in axial velocity which is commonly referred to as 'rebound'. One explanation of this phenomenon suggests that it is essentially an inviscid process because of the finite core-size, whereas another and more widely accepted explanation attributes it to the influence of a secondary vortex which is generated at the surface by viscous effects. The aim of this paper is to assess experimentally the validity of these competing explanations. To achieve this, flow visualization studies of the collision of a vortex ring with a wall are compared with those of the head-on collision of two identical rings. The head-on collision is designed to mimic the inviscid, free-slip case of a ring/wall interaction. This paper describes the experimental findings.

Lin, M., Cui, G. and Zhang, Z.

"A NEW VORTEX SHEET MODEL FOR SIMULATING AIRCRAFT WAKE VORTEX EVOLUTION"

Chinese Journal of Aeronautics, Vol. 30, No. 4, 2017, pp. 1315-1326.

A new vortex sheet model was proposed for simulating aircraft wake vortex evolution. Rather than beginning with a pair of counter-rotating cylindrical vortices as in the traditional models, a lift-drag method is used to initialize a vortex sheet so that the roll-up phase is considered. The results of this model report a better approximation to a real situation when compared to the measurement data. The roll-up induced structures are proved to influence the far-field decay. On one hand, they lead to an early decay in the diffusion phase. On the other hand, the growth of linear instability such as elliptical instability is suppressed, resulting in a slower decay in the rapid decay phase. This work provides a simple and practicable model for simulating wake vortex evolution, which combines the roll-up process

and the far-field phase in simulation. It is also proved that the roll-up phase should not be ignored when simulating the far-field evolution of an aircraft wake vortex pair, which indicates the necessity of this new model.

Lin, M., Cui, G. and Zhang, Z.

"LARGE EDDY SIMULATION OF AIRCRAFT WAKE VORTEX WITH SELF-ADAPTIVE GRID METHOD"

Applied Mathematics and Mechanics, Vol. 37, No. 10, 2016, pp. 1289-1304.

A self-adaptive-grid method is applied to numerical simulation of the evolution of aircraft wake vortex with the large eddy simulation (LES). The Idaho Falls (IDF) measurement of run 9 case is simulated numerically and compared with that of the field experimental data. The comparison shows that the method is reliable in the complex atmospheric environment with crosswind and ground effect. In addition, six cases with different ambient atmospheric turbulences and Brunt Vaisala (BV) frequencies are compared with the LES. The main characteristics of vortex are appropriately simulated by the current method. The onset time of rapid decay and the descending of vortices agree with the previous measurements and the numerical prediction. Also, secondary structures such as baroclinic vorticity and helical structures are also simulated. Only approximately 6 million grid points are needed in computation with the present method, while the number can be as large as 34 million when using a uniform mesh with the same core resolution. The self-adaptive-grid method is proved to be practical in the numerical research of aircraft wake vortex.

Lin, M., Huang, W., Zhang, Z., Xu, C. and Cui, G.

"NUMERICAL STUDY OF AIRCRAFT WAKE VORTEX EVOLUTION NEAR GROUND IN STABLE ATMOSPHERIC BOUNDARY LAYER"

Chinese Journal of Aeronautics, Vol. 30, No. 6, 2017, pp. 1866-1876.

The evolution of aircraft wake vortices near the ground in stable atmospheric boundary layer are studied by Large Eddy Simulation (LES). The sensitivity of vortex evolution to the Monin-Obukhov (M-O) scale is studied for the first time. The results indicate that increasing stability leads to longer lifetimes of upwind vortices, while downwind vortices will decay faster due to a stronger crosswind shear under stable conditions. Based on these results, an empirical model of the vortex lifetime as a function of 10-m-high crosswind and the M-O scale is summarized. This model can provide an estimate of the upper boundary of the vortex lifetime according to the real-time crosswind and atmospheric stability. In addition, the lateral translation of vortices is also inspected. The results show that vortices can travel a furthest distance of 722 m in the currently-studied parameter range. This result is meaningful to safety analysis of airports that have parallel runways.

Lin, Y.-L.

"INSTABILITIES CONDUCIVE TO AVIATION TURBULENCE"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 3, 2016, Springer International Publishing Switzerland, pp. 59-82.

Atmospheric instabilities, including static, Kelvin-Helmholtz (KHL), inertial, conditional, potential (convective), symmetric, conditional symmetric, and potential symmetric instabilities, might trigger aviation-scale turbulence such as the clear-air turbulence (CAT), mountain wave turbulence (MWT), and near-cloud turbulence (NCT) that are reviewed in this chapter. Energy conversion associated with several atmospheric instabilities is reviewed through an equation governing energy transfer in an inviscid, stably stratified shear flow, and the Taylor-Goldstein equation is used to prove a corollary of Howard's semicircle theorem and the Miles-Howard Theorem. The criteria for static (gravitational) instability, conditional instability, potential instability, inertial instability, symmetric instability, conditional symmetric instability, and potential symmetric instability are discussed and summarized in a table. Their implications for the development of turbulence diagnostics or indices for aviation turbulence forecasting are also discussed.

Lin, Y.-L., Arya, S. P. and Kaplan, M. L.

"NUMERICAL MODELING STUDIES OF WAKE VORTEX TRANSPORT AND EVOLUTION WITHIN THE PLANETARY BOUNDARY LAYER"

NASA-CR-196078, January 1994, North Carolina State University, Raleigh, NC

The proposed research involves four tasks. The first of these is to simulate accurately the turbulent processes in the atmospheric boundary layer. TASS was originally developed to study meso-gamma scale phenomena, such as tornadic storms, microbursts, and windshear effects in terminal areas. Simulation of wake vortex evolution, however, will rely on appropriate representation of the physical processes in the surface layer and mixed layer. This involves two parts. First, a specified heat flux boundary condition must be implemented at the surface. Using this boundary condition, simulation results will be compared to experimental data and to other model results for validation. At this point, any necessary changes to the model will be implemented. Next, a surface energy budget parameterization will be added to the model. This will enable calculation of the surface fluxes by accounting for the radiative heat transfer to and from the ground and heat loss to the soil rather than simple specification of the fluxes. The second task involves running TASS with prescribed wake vortices in the initial condition. The vortex models will be supplied by NASA Langley Research Center. Sensitivity tests will be performed on different meteorological environments in the atmospheric boundary layer, which include stable, neutral, and unstable stratifications, calm and severe wind conditions, and dry and wet conditions. Vortex strength may be varied as well. Relevant non-dimensional parameters will include the following: Richardson number or Froude number, Bowen ratio, and height to length scale ratios. The model output will be analyzed and visualized to better understand the transport, decay, and growth rates of the wake vortices. The third task involves running simulations using observed data. MIT Lincoln Labs is currently planning field experiments at the Memphis airport to measure both meteorological conditions and wake vortex characteristics. Once this data becomes available, it can be used to validate the model for vortex behavior under different atmospheric conditions. The fourth task will be to simulate the wake in a more realistic environment covering a wider area. This will involve grid nesting, since high resolution will be required in the wake

region but a larger total domain will be used. During the first allocation year, most of the first task will be accomplished.

Lin, Y.-L., Arya, S. P., Kaplan, M. L. and Shen, S.

"NUMERICAL MODELING STUDIES OF WAKE VORTEX TRANSPORT AND EVOLUTION WITHIN THE PLANETARY BOUNDARY LAYER"

NASA/CR-1998-207826, April 1, 1998, North Carolina State University, Raleigh, NC

In support of the wake vortex effect of the Terminal Area Productivity program, we have put forward four tasks to be accomplished in our proposal. The first task is validation of two-dimensional wake vortex-turbulence interaction. The second task is investigation of three-dimensional interaction between wake vortices and atmospheric boundary layer (ABL) turbulence. The third task is ABL studies. The fourth task is addition of a Klemp-Durran condition at the top boundary for TASS model. The accomplishment of these tasks will increase our understanding of the dynamics of wake vortex and improve forecasting systems responsible for air safety and efficiency. The first two tasks include following three parts: (a) Determine significant length scale for vortex decay and transport, especially the length scales associated with the onset of Crow instability; (b) Study the effects of atmospheric turbulence on the decay of the wake vortices; and (c) Determine the relationships between decay rate, transport properties and atmospheric parameters based on large eddy simulation (LES) results and the observational data. These parameters may include turbulence kinetic energy, dissipation rate, wind shear and atmospheric stratification. The ABL studies cover LES modeling of turbulence structure within planetary boundary layer under transition and stable stratification conditions. Evidences have shown that the turbulence in the stable boundary layer can be highly intermittent and the length scales of eddies are very small compared to those in convective case. We proposed to develop a nesting grid mesh scheme and a modified Klemp-Durran condition at the top boundary for TASS model to simulate planetary boundary layer under stable stratification conditions.

Lin, Y.-L., Han, J., Zhang, J, Ding, F. and Arya, S. P.

"LARGE EDDY SIMULATION OF WAKE VORTICES IN THE CONVECTIVE BOUNDARY LAYER"

AIAA Paper No. 2000-0753, Reno, NV, January 2000

The behavior of wake vortices in a convective boundary layer is investigated using a validated large eddy simulation model. Our results show that the vortices are largely deformed due to strong turbulent eddy motion while a sinusoidal Crow instability develops. Vortex rising is found to be caused by the updrafts (thermals) during daytime convective conditions and increases with increasing nondimensional turbulence intensity n . In the downdraft region of the convective boundary layer, vortex sinking is found to be accelerated proportional to increasing n , with faster speed than that in an ideal line vortex pair in an inviscid fluid. Wake vortices are also shown to be laterally transported over a significant distance due to large turbulent eddy motion. On the other hand, the decay rate of the

vortices in the convective boundary layer that increases with increasing n , is larger in the updraft region than in the downdraft region because of stronger turbulence in the updraft region.

Lindelow, P.

"FIBER BASED COHERENT LIDARS FOR REMOTE WIND SENSING"

PhD Thesis, November 2007, University of Denmark, Lyngby, Denmark.

In this thesis a study of coherent lidars for remote wind sensing is undertaken. Remote wind sensing is important when mast mounted anemometers cannot be used due to economical or practical reasons. One such important field is within the wind energy sector where accurate wind sensing at distances of up to a few hundred meters from the ground is important for site evaluation, turbine power verification and for future applications such as active blade pitch and load control for an optimized output. The thesis covers a wide field; the state-of-the-art coherent lidar wind sensors is reviewed, the signal model is expanded upon and results of applied research on commercially available lidars, as well as the development and evaluation of a frequency modulated prototype, are presented. The standard model for coherent lidars sensing dispersed targets was expanded upon by considering the range dependent correlated contribution duration of range gated systems, which significantly affects the narrowband signal to noise description and the weighting of the sample volume. A model of the range dependent collection efficiency obtained by focused fiber based lidars has been developed and verified. These advancements are important for predicting the lidar performance and optimizing the signal processing. A novel frequency modulation concept, which is promising for the remote sensing of wind, was invented in this study. The technique is based on equidistantly frequency stepped pulse trains and a frequency pursuing local oscillator. It operates at high pulse repetition but will despite this avoid the customary disadvantages, range ambiguity and a limitation of the sensing range. This novel concept could provide more accurate systems while avoiding the use of high peak powers which introduces stimulated Brillouin scattering and non-linear effects as well as higher demands on other components in the transmitter. A frequency sweeper, appropriate for the invented frequency modulation technique, was constructed and evaluated. This sweeper was subsequently used to modify a continuous wave lidar into a frequency modulated prototype and a proof of principle campaign, demonstrated the merits and limitations of the novel technique.

Line, A. J. and Brown, R. E.

"HIGH RESOLUTION WAKE MODELLING USING A SEMI-LAGRANGIAN ADAPTIVE GRID FORMULATION"

European Rotorcraft Forum, Friedrichshafen, Germany, September 2003

Current interest in improving numerical predictions of helicopter rotor vibration and acoustic signature has driven a requirement to model blade aerodynamic loadings to extremely high resolution. The problem is complicated by the complexity of the flow in the rotor wake and the difficulty in conserving vortical structures in the wake for long enough so that all important vibration- or noise-producing blade vortex interactions are represented properly. The Vorticity Transport Model,

developed by Brown, can preserve vortical structures over sufficiently long timescales, but, up to now, has been prohibitively expensive when run at the resolutions required for accurate vibration or acoustic prediction. In this paper we present a new computational grid system which, using adaptive cell management and nested grids, allows significant increases in grid resolution with minimal impact on computational cost. The new grid system is effectively boundary-free, thus eliminating the need for numerical boundary conditions. In addition, the velocity field is optimally evaluated on the new grid using an extremely efficient technique based on the Cartesian Fast Multipole Method. The implementation of both the grid system and the velocity calculation within a new version of the Vorticity Transport Model is described. The performance of the new model is validated against experimental data and some properties of the model, when used to predict rotor loads to a resolution that approaches that required for calculations of rotor vibration or acoustic signature, are illustrated.

Liou, S. G., Komerath, N. M. and McMahon, H. M.

"VELOCITY FIELD OF A CYLINDER IN THE WAKE OF A ROTOR IN FORWARD FLIGHT"

J. Aircraft, Vol. 27, No. 9, September 1990, pp. 804-809

The rotor and the airframe of a rotorcraft can have severe effects on each other because of flowfield interactions. Data on flowfield characteristics have been obtained using laser velocimetry to identify and interpret the features of such interactions. This paper summarizes previous results on the flowfield of the rotor and then describes the effects of the rotor wake on the flowfield around an airframe model. A circular cylinder with a hemispherical nose is used as the airframe model and is instrumented with static pressure taps and flush-mounted microphones. A two-bladed teetering rotor is suspended above it in a wind tunnel. The periodic and time-averaged velocity fields are measured along lines parallel to the airframe axis at a rotor advance ratio of 0.1 and a rotor tip Mach number of 0.29. The dominant features in the velocity distribution over the airframe are seen to be linked to vortex interactions with the airframe surface. The tip vortex and the trailing vortex sheet are seen to be displaced in opposite directions by the airframe. Secondary vortex generation phenomena are observed near the airframe surface during vortex interaction.

Liow, Y. S. K., Thompson, M. C. and Hourigan, K.

"SOUND GENERATED BY A PAIR OF AXISYMMETRIC COAXIAL VORTEX RINGS"

AIAA Journal, Vol. 43, No. 2, February 2005, pp. 326-336

The time-dependent acoustic field generated by the mutual interaction of a pair of coaxial viscous vortex rings advecting along a common axis of symmetry is simulated using a two-step numerical procedure. In the first step, the flowfield is predicted by solving the incompressible Navier-Stokes equations. In the second step, Powell's vortex sound theory is used to predict the far-field acoustic field associated with the flow unsteadiness. This study considers the effect of the initial toroidal ring radii on the sound radiation. The acoustic predictions are compared with those obtained using the method of matched asymptotic expansions. Our results indicate that the acoustic signature for the

Mach-number range simulated shows an axisymmetric lateral quadrupole pattern. In addition, the time variation of the far-field acoustic signal displays significant effects caused by vortex dynamics associated with the finite-sized cores and viscous diffusion. These effects are more pronounced for rings with a smaller initial toroidal radius. The influence of Mach number on the far-field directivity (e.g., location of polar extinction angles) and the multipole content of the acoustic signal is examined through a multiple decomposition of the predicted acoustic fields.

Lissaman, P. B. S., Crow, S. C., MacCready, Jr., P. B., Tombach, I. H. and Bate Jr., E. R.

"AIRCRAFT VORTEX WAKE DESCENT AND DECAY UNDER REAL ATMOSPHERIC EFFECTS"

FAA-RD-73-120, October 1973, AeroVironment Inc., Pasadena, CA

Aircraft vortex wake descent and decay in a real atmosphere is studied analytically. Factors relating to encounter hazard, wake generation, wake descent and stability, and atmospheric dynamics are considered. A new analysis for Crow instability in ambient turbulence is given, expressing time-to-linkage as an explicit function of the turbulent dissipation. Wake descent in a stratified inviscid fluid is studied analytically providing new results. According to the new theory, the vortex span reduces upon descent into a stably stratified flow, causing the rate of descent to increase. Exact solutions are derived for vortex cell shapes in a uniformly sheared crosswind, showing that the upwind cell is greatly increased in size. It is believed that this may partly account for the observed unsymmetrical behavior (banking, etc.) in crosswinds.

Liu, B., Byon, E. and Plumlee, M.

"DATA-DRIVEN PARAMETER CALIBRATION IN WAKE MODELS"

AIAA Paper 2018-2017, January 2018, Kissimmee, FL.

Physical interactions among wind turbines, called wake effects, are known to be one of the significant factors that affect power generation performance in wind power systems. Among several wake modeling approaches, physics-based engineering models, such as Jensen's model, have been widely used due to their computational tractability. Although substantial efforts have been made to improve the accuracy of engineering wake models, few studies suggest calibrating the model parameters in the literature. We propose a new data-driven calibration approach for adjusting the model parameters using real operational data.

Liu, C.

"WAKE VORTEX ENCOUNTER ANALYSIS WITH DIFFERENT WAKE VORTEX MODELS USING VORTEX-LATTICE METHOD"

MS Thesis, Delft University of Technology, Delft, The Netherlands, Dec. 2007

The objective of the present study is to program a reliable MathCAD code based on the Vortex Lattice Method (VLM) to calculate the induced rolling moment on an aircraft during wake vortex encounters (WVEs). The code is named Chaos because of the complexity of WVEs. As part of the present work, nine different vortex profiles are compared throughout their properties. The maximum induced rolling moment depends on the vortex model, the core radius and the vortex spacing. A short distance behind the wing of an aircraft the cross-flow kinetic energy of the vortex pair is directly related to the induced drag of the wing and this provides a condition for the initial vortex core size. Starting from this point, the decay of the vortex core radius can be calculated with an effective viscosity turbulence model (Owen 1970). Moreover, the decay of the wake vortex circulation and decay of induced rolling moment (an empirical equation from Winckelmans (2004) can be obtained. For different vortex models, all the different decays are compared numerically in this report. It was found that the nine different vortex profiles do not cause very big differences for the induced rolling moment coefficient analysis, especially for bigger follower aircraft.

Liu, C. H.

"A THREE-DIMENSIONAL VORTEX PARTICLE-IN-CELL METHOD FOR VORTEX MOTIONS IN THE VICINITY OF A WALL"

International J. for Numerical Methods in Fluids, Vol. 37, November 2001, pp. 501-523

A new vortex particle-in-cell method for the simulation of three-dimensional unsteady incompressible viscous flow is presented. The projection of the vortex strengths onto the mesh is based on volume interpolation. The convection of vorticity is treated as a Lagrangian move operation but one where the velocity of each particle is interpolated from an Eulerian mesh solution of velocity-Poisson equations. The change in vorticity due to diffusion is also computed on the Eulerian mesh and projected back to the particles. Where diffusive fluxes cause vorticity to enter a cell not already containing any particles new particles are created. The surface vorticity and the cancellation of tangential velocity at the plate are related by the Neumann conditions. The basic framework for implementation of the procedure is also introduced where the solution update comprises a sequence of two fractional steps. The method is applied to a problem where an unsteady boundary layer develops under the impact of a vortex ring and comparison is made with the experimental and numerical literature.

Liu, C. H. and Ting, L.

"INTERACTION OF DECAYING TRAILING VORTICES IN SPANWISE SHEAR FLOW"

Computers & Fluids, Vol. 15, No. 4, 1987, pp. 77-92.

The drift of trailing vortices in a cross wind near the ground is modeled by an unsteady two-dimensional, rotational flowfield where there are concentrations of large vorticity in spots having small effective sizes and finite total strengths. The problem is analyzed by combining the matched asymptotic solution of the decaying vortical spots and the Euler solution of the background unsteady rotational flow. Using the method of averaging, we develop a numerical scheme in which the grid size

and time step depend only on the length and velocity scales of the background flow and not on the effective core size of vertical spots. Numerical results are presented to illustrate the interaction between the trajectories of the vertical spots and the convection of vorticity in the background flowfield.

Liu, C. H. and Ting, L.

"MOTION, DECAY AND MERGING OF VORTEX FILAMENTS"

Southeastern Conference on Theoretical and Applied Mechanics, April 1988, Biloxi, MS.

The asymptotic solutions of Navier-Stokes equations for vortex filaments of finite strength with small effective vortical cores are summarized. Emphases are placed on the physical meaning and the practical limit to the applicability of the asymptotic solution. Finite-difference solutions of Navier-Stokes equations for the merging of the filament(s) are described. It is focused on the development of the approximate boundary conditions for the computational domain.

Liu, C. H., Kandil, O. A. and Kandil, H. A.

"NUMERICAL SIMULATION AND PHYSICAL ASPECTS OF SUPERSONIC VORTEX BREAKDOWN"

Computers Fluids, Vol. 22, No. 4/5, 1993, pp. 607-622.

Existing numerical simulations and physical aspects of subsonic and supersonic vortex-breakdown modes are reviewed. The solution to the problem of supersonic vortex breakdown is emphasized in this paper and carried out with the full Navier-Stokes equations for compressible flows. Numerical simulations of vortex-breakdown modes are presented in bounded and unbounded domains. The effects of different types of downstream-exit boundary conditions are studied and discussed.

Liu, C. H., Krause, E. and Menne, S.

"ADMISSIBLE UPSTREAM CONDITIONS FOR SLENDER COMPRESSIBLE VORTICES"

AIAA Paper No. 1986-1093, May 1986, Atlanta, GA.

The influence of the compressibility on the flow in slender vortices is being studied. The dependence of the breakdown of the slender-vortex approximation on the upstream conditions is demonstrated for various Reynolds numbers and Mach numbers. Compatibility conditions, which have to be satisfied if the vortex is to remain slender, are discussed in detail. The general discussions are supplemented by several sample calculations.

Liu, C. H., Tavantzis, J. and Ting, L.

"NUMERICAL STUDIES OF MOTION AND DECAY OF VORTEX FILAMENTS"

AIAA Journal, Vol. 24, No. 8, August 1986, pp. 1290-1297.

A computational code is developed for the integro-differential equations governing the motion of the centerlines of vortex filaments submerged in a background potential flow. These equations, which are derived from the method of matched asymptotic analysis, include the effect of decaying large-magnitude circumferential and axial velocity components in the vortical cores. Numerical examples are presented to assess the effect of large axial velocity and of non-similar initial profiles in vortical cores. The initial configurations of the filaments are chosen so as to fulfill the basic assumptions of asymptotic analysis, which is the effective vortical core size is much smaller than all other length scales in the flowfield, e.g., the radius of curvature and interfilament distance. The computations are continued until the basic assumption is no longer valid, that is, when the merging or interaction of filaments have begun. Various types of local or global merging or interaction of filaments are classified and demonstrated by numerical examples.

Liu, C. H., Thomas, J. L. and Tung, C.

"NAVIER-STOKES CALCULATIONS FOR THE VORTEX WAKE OF A ROTOR IN HOVER"

AIAA Paper No. 1983-1676, Danvers, MA, July 1983

An efficient finite-difference scheme for the solution of the incompressible Navier-Stokes equation is used to study the vortex wake of a rotor in hover. The solution procedure uses a vorticity-stream function formulation and incorporates an asymptotic far-field boundary condition enabling the size of the computational domain to be reduced in comparison to other methods. The results from the present method are compared with experimental data obtained by smoke flow visualization and hot-wire measurements for several rotor blade configurations.

Liu, C.-H. and Ting, L.

"MOTION AND INTERACTION OF DECAYING TRAILING VORTICES IN SPANWISE SHEAR WIND"

NASA TP-2599, September 1986, NASA Langley Research Center, Hampton, VA.

This paper presents a simulation of the drift of trailing vortices in a cross-wind near the ground by an unsteady, two-dimensional, rotational flow field with a concentration of large vorticity in 'vortical spots' (having a finite but small effective size and finite total strength). The problem is analyzed by a combination of the method of matched asymptotic analyses for the decay of the vortical spots and the Euler solution for the unsteady rotational flow. Using the method of averaging, a special numerical method is developed in which the grid size and time step depend only on the length and velocity scales of the background flow and independent of the effective core size of a vortical spot. The core size can be much smaller than the grid size, whereas the peak velocity in the core is inversely proportional to the spot size. Numerical results are presented to demonstrate the strong interaction between the trajectories of the vortical spots and the change of the vorticity distribution in the background flow field.

Liu, G. C. and Ting, L.

"NUMERICAL STUDIES OF THE MARGIN OF VORTICES WITH DECAYING CORES"

AIAA Paper No. 1986-1072, Atlanta, GA, May 1986

The merging of vortices to one vortex is a canonical incompressible viscous flow problem. The merging process begins when the core sizes or the vortices are comparable to their distances and ends when the contour lines of constant vorticity lines are circularized around one center. Approximate solutions to this problem are constructed by adapting the asymptotic solutions for distinct vortices. For the early stage of merging, the next-order terms in the asymptotic solutions are added to the leading term. For the later stage of merging, the vorticity distribution is reinitialized by vortices with overlapping core structures guided by the 'rule of merging' and the velocity of the 'vortex centers' are then defined by a minimum principle. To show the accuracy of the approximate solution, it is compared with the finite-difference solution.

Liu, H.

"INTERFACING COMPREHENSIVE ROTORCRAFT ANALYSIS WITH ADVANCED AEROMECHANICS AND VORTEX WAKE MODELS"

MS Thesis, Dec. 2007, Georgia Institute of Technology, Atlanta, GA.

This dissertation describes three aspects of the comprehensive rotorcraft analysis. First, a physics-based methodology for the modeling of hydraulic devices within multibody-based comprehensive models of rotorcraft systems is developed. This newly proposed approach can predict the fully nonlinear behavior of hydraulic devices, and pressure levels in the hydraulic chambers are coupled with the dynamic response of the system. The second part of this research is in computational aeroelasticity, in which an interface between computational fluid dynamics (CFD) and computational structural dynamics (CSD) is established. This interface enables data exchange between CFD and CSD with the goal of achieving accurate air loads predictions. The ability to accurately capture the wake structure around a helicopter rotor is crucial for rotorcraft performance analysis. In the third part of this thesis, a new representation of the wake vortex structure based on Non-Uniform Rational B-Spline curves and surfaces is proposed to develop an efficient model for prescribed and free wakes. The proposed formulation has the potential to reduce the computational cost associated with the use of the Helmholtz law and the Biot-Savart law when calculating the induced flow field around the rotor. An efficient free wake analysis will considerably decrease the computational cost of comprehensive rotorcraft analysis, making the approach more attractive to routine use in industrial settings.

Liu, H.

"INTERFACING COMPREHENSIVE ROTORCRAFT ANALYSIS WITH ADVANCED AEROMECHANICS AND VORTEX WAKE MODELS"

Ph.D. Thesis, April 2008, Georgia Institute of Technology, Atlanta, GA.

This dissertation describes three aspects of the comprehensive rotorcraft analysis. First, a physics-based methodology for the modeling of hydraulic devices within multibody-based comprehensive models of rotorcraft systems is developed. This newly proposed approach can predict the fully nonlinear behavior of hydraulic devices, and pressure levels in the hydraulic chambers are coupled with the dynamic response of the system. The second part of this research is in the area of computational aeroelasticity, in which an interface between computational fluid dynamics (CFD) and computational structural dynamics (CSD) is established. This interface enables data exchange between CFD and CSD with the goal of achieving accurate air loads predictions. The ability to accurately capture the wake structure around a helicopter rotor is crucial for rotorcraft performance analysis. In the third part of this thesis, a new representation of the wake vortex structure based on Non-Uniform Rational B-Spline curves and surfaces is proposed to develop an efficient model for prescribed and free wakes. The proposed formulation has the potential to reduce the computational cost associated with the use of the Helmholtz law and the Biot-Savart law when calculating the induced flow field around the rotor. An efficient free wake analysis will considerably decrease the computational cost of comprehensive rotorcraft analysis, making the approach more attractive to routine use in industrial settings.

Liu, H. T.

"LABORATORY INVESTIGATION OF ATMOSPHERIC EFFECTS ON VORTEX WAKES"

Report DTRS-57-87-C-00109, February 1990, Flow Research, Inc., Kent, WA.

Tow tank experiments were conducted to investigate atmospheric effects on the evolution of trailing vortex wakes. The atmospheric effects simulated in the tank included stable stratification, ambient turbulence, and wind shear. The rebound phenomenon of a vortex wake approaching the ground surface was also investigated. Two methods were used to generate vortex wakes: a towed NACA 0012 wing and a 2-D vortex generator.

Liu, H.-T.

"LABORATORY INVESTIGATION OF DETRAINMENT IN VORTEX WAKES"

AIAA Journal, Vol. 44, No. 8, August 2006, pp. 1872-1882

Detrainment in vortex wakes is a delicate phenomenon that has been predicted to occur only at high Froude numbers in stratified fluids, because of imbalance of buoyancy between fluids inside and outside the vortex wakes. Such a phenomenon rarely manifests in full-scale flights because the required high-Froude-number conditions are seldom met. Physical modeling of the phenomenon using small-scale wings must be conducted in a fluid with a very weak stratification, which is difficult to prepare and maintain in the laboratory. Furthermore, the detrainment flow is so weak that its observation relies on the generation of very clean vortex wakes. Consequently, only limited laboratory results are available and the phenomenon is by no means well understood. Detrainment in vortex wakes has not been observed directly but inferred from their kinematics, that is, acceleration and

deceleration. The first ever visual evidence of the detrainment phenomenon is provided. The stringent requirements were met by 1) conducting towing-tank experiments using a two-dimensional vortex generator and a clean wing model suspended on fine wires and 2) preparing weakly stratified fluids using brine and/or heat. Based on visual results effects of detrainment on the vortex wakes were studied qualitatively and quantitatively.

Liu, H.-T.

"LABORATORY INVESTIGATION OF ATMOSPHERIC EFFECTS ON VORTEX WAKES -A FEASIBILITY INVESTIGATION"

TR 394, March 1987, Flow Research, Inc., Kent, WA

Tow tank experiments were successfully conducted to demonstrate the feasibility of investigating atmospheric effects on the evolution of a trailing vortex wake. Atmospheric disturbances simulated in the tank included stable stratification, ambient turbulence, and wind shear. Visualizations of the vortex wakes from several perspectives were conducted using fluorescent dye illuminated by bands of ultraviolet lights and a sheet of laser light. In a quiescent environment, we have established the upper bound of the lifespan of a trailing vortex wake due to essentially self-induced sinusoidal instability. Ambient turbulence reduces the lifespan. Vortex linking is the dominant mode of vortex instability in weak turbulence. As the turbulence intensity or dissipation rate increases, vortex bursting begins to appear and eventually replaces linking as the dominant mode of instability. The wind shear affects the behavior of the vortex wake in two ways. In a longitudinal shear, the inclined trailing vortex pair is stretched, resulting in vortex contraction and leading to speed up of vortex descent and possibly to vortex annihilation prior to the onset of linking or bursting. In a cross shear, the vortex wake is forced to rotate about its axis.

Liu, H.-T.

"EFFECTS OF AMBIENT TURBULENCE ON THE DECAY OF A TRAILING VORTEX WAKE"

Journal of Aircraft, Vol. 29, No. 2, Mar.-Apr. 1992, pp. 255-263

Experiments were conducted to investigate the effects of ambient turbulence on the evolution of a trailing vortex wake. The wake was generated by towing an NACA 0012 wing, with a span of 10.2 cm and a chord of 5.1 cm, at an incidence of -10 deg and a speed of 40 cm/s in a tow tank. The chord Reynolds number was 20,400. The ambient turbulence was generated by towing three grids, with square meshes of 1.45, 10.2, and 20.3 cm, upstream of the wing. Turbulence parameters were measured with crossed hot-film probes. The trailing vortex wake, tagged with a fluorescent dye, was visualized from different perspectives and its decay was derived from 16-mm movie records. For weak turbulence with large integral scales compared with the vortex separation, vortex linking is the dominant mode of instability. The dominant wavelength of the linking decreases with increasing turbulence intensity or dissipation rate. As the turbulence intensity increases, vortex bursting appears and eventually replaces linking as the dominant mode of instability. For turbulence with a small

integral scale as compared with the vortex separation, vortex instability is predominantly of the bursting type.

Liu, H.-T.

"TOW-TANK SIMULATION OF VORTEX WAKE DYNAMICS"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 32-1 - 32-26

Towing tank experiments were conducted to investigate ambient and ground effects on vortex wakes. Two methods were used to generate the vortex wakes: a towed NACA 0012 wing with a chord Reynolds number of 20,400 and a slotted-jet vortex generator. The ambient turbulence was generated by towing upstream of the wing three grids of different meshes. Turbulence parameters were measured with crossed hot-film probes. The trailing vortex wake, tagged with a fluorescent dye, was visualized and its evolution was derived from 16-mm movie records. For weak turbulence with large integral scales compared with the vortex separation, vortex linking is the dominant mode of instability. The dominant wavelength of the linking decreases with increasing turbulence intensity or dissipation rate. As the turbulence intensity increases, vortex bursting appears and eventually replaces linking as the dominant mode of instability. For turbulence with a small integral scale as compared with the vortex separation, vortex instability is predominantly of the bursting type. Trajectories derived from trailing vortex wakes near a simulated ground surface have confirmed the inadequacy of the two-dimensional inviscid solution. The generation of a relatively weak secondary vortex causes the primary vortex to rebound from the surface as a result of unsteady separation. For the slotted-jet vortex generator, the introduction of a rigid surface close to the jet exit results in the formation of relatively strong and persistent secondary vortices at the ground outboard of the primary vortices. A simple modification of the two-dimensional inviscid theory -- namely, adding a secondary vortex to the system -- recreates the rebound phenomenon, which agrees qualitatively with the trend seen in the experiments.

Liu, H.-T. and Srnsky, R. A.

"LABORATORY INVESTIGATION OF ATMOSPHERIC EFFECTS ON VORTEX WAKES"

TR 497, February 1990, Flow Research, Inc., Kent, WA

Tow tank experiments were conducted to investigate atmospheric effects on the evolution of trailing vortex wakes. The atmospheric effects simulated in the tank included stable stratification, ambient turbulence, and wind shear. In a quiescent fluid, self-induced sinusoidal instability limits the lifespan of a trailing vortex wake in a neutral or weakly stratified environment. Ambient turbulence reduces the lifespan. For weak turbulence with a large integral scale compared with the vortex separation, vortex linking is the dominant mode of vortex instability. As the turbulence intensity or dissipation rate increases, however, vortex bursting begins to appear and eventually replaces linking as the dominant mode of instability. Existing theory tends to underpredict, by a factor of about 2, the lifespan of the vortex wake in a turbulent environment. For turbulence with a small integral scale compared with the

vortex separation, vortex instability is predominantly of the bursting type. In a longitudinal shear, the inclined trailing vortex pair tends to be stretched, resulting in an increase in the dominant wavelength of the linking instability. In a cross shear, one side of the vortex pair is stabilized and the other destabilized by the shear, the formation of a solitary vortex at large times is often observed. Tipping of the vortex wake is observed just below the exit of the 2-D vortex pair due to the presence of a crossflow. The tipping is attributed to the asymmetries of the initial rollup and of the flow generated as the vortex pair is carried by the crossflow across the exit plate. There is no correlation between the orientation of the tipping and the sign of the shear flow. With respect to ground effects, a vortex wake rebounds after it moves close to the ground. By introducing a solid surface close to the exit of the 2-D vortex pair, the formation of secondary vortices outboard of the main vortices that cause the latter to rebound is evident from the visual results. Trajectories derived from the trailing vortex wake released in the proximity of a simulated ground surface have confirmed that the hyperbolic inviscid solution is incorrect.

Liu, H.-T., Hwang, P. A. and Srnsky, R. A.

"PHYSICAL MODELING OF GROUND EFFECTS ON VORTEX WAKES"

Journal of Aircraft, Vol. 29, No. 6, November-December 1992, pp. 1027-1034.

Towing-tank experiments were conducted to investigate ground effects on vortex wakes. Two methods were used to generate the vortex wakes: 1) a towed NACA 0012 wing and 2) a slotted-jet vortex generator. Trajectories derived from trailing vortex wakes, tagged with a fluorescent dye and released near the simulated ground surface, have confirmed the inadequacy of the two-dimensional inviscid solution. The generation of a relatively weak secondary vortex causes the primary vortex to rebound from the surface because of unsteady separation. There is no significant difference between the trajectories, whether the ground is simulated by a rigid surface or a free surface. The introduction of a rigid surface close to the exit of the slotted-jet vortex generator results in the formation of secondary vortices at the ground outboard of the primary vortices. The secondary vortices generated by the slotted-jet vortex pair are more coherent and persistent than those generated by the trailing vortex pair. A simple modification of the two-dimensional inviscid theory -namely, adding a secondary vortex to the system - recreates the rebound phenomenon, which agrees qualitatively with the trend seen in the experiments.

Liu, J., Piomelli, U. and Spalart, P. R.

"INTERACTION BETWEEN A SPATIALLY GROWING TURBULENT BOUNDARY LAYER AND EMBEDDED STREAMWISE VORTICES"

Journal of Fluid Mechanics, Vol. 326, 1996, pp. 151-179.

The interaction between a zero-pressure-gradient turbulent boundary layer and a pair of strong, common-flow-down, streamwise vortices with a sizable velocity deficit is studied by large-eddy simulation. The sub-grid-scale stresses are modelled by a localized dynamic eddy-viscosity model. The

results agree well with experimental data. The vortices drastically distort the boundary layer, and produce large spanwise variations of the skin friction. The Reynolds stresses are highly three-dimensional. High levels of kinetic energy are found both in the upwash region and in the vortex core. The two secondary shear stresses are significant in the vortex region, with magnitudes comparable to the primary one. Turbulent transport from the immediate upwash region is partly responsible for the high levels of turbulent kinetic energy in the vortex core; its effect on the primary stress ($u'v'$) is less significant. The mean velocity gradients play an important role in the generation of ($u'v'$) in all regions, while they are negligible in the generation of turbulent kinetic energy in the vortex core. The pressure-strain correlations are generally of opposite sign to the production terms except in the vortex core, where they have the same sign as the production term in the budget of ($u'v'$). The results highlight the limitations of the eddy-viscosity assumption (in a Reynolds-averaged context) for flows of this type, as well as the excessive diffusion predicted by typical turbulence models.

Liu, P.-Q., Wen, R.-Y. and Zhang, G.-W.

"EFFECTS OF CANARD SWEEP AND CANARD-SPANWISE BLOWING MAGNITUDE ON LIFT INCREMENT"

Journal of Aircraft, Vol. 43, No. 5, September-October 2006, pp. 1369-1371.

The effects of different canard's swept angles and jet momentum coefficients on the lift increment of simple close-coupled canard configurations with a 40-deg swept delta wing were investigated in a low-speed wind tunnel by force measurement. The experimental results show that at a certain range of attack angles (16-50 deg), on the condition of no blowing, with the increasing of the canard's swept angles, the lift increment and critical stall angles increase, which shows that the canard can be used as a controlling element for aerodynamic forces. On the condition of blowing, when the jet momentum coefficient exceeds a certain value, the more the jet momentum coefficient is, the more the lift increment is, which suggests that indirectly controlling the wing vortex is possible by canard-spanwise blowing for close-coupled canard configurations.

Liu, X. and Marshall, J. S.

"BLADE PENETRATION INTO A VORTEX CORE WITH AND WITHOUT AXIAL CORE FLOW"

J. Fluid Mech., Vol. 519, 2004, pp. 81-103

A computational study of the penetration of a blade into the core of an initially columnar vortex in an incompressible viscous fluid and the subsequent cutting of the vortex is reported for the case where the blade axis is initially orthogonal to the vortex axis. The vortex is advected toward the fixed blade by a free-stream velocity-oriented tangent to the blade chord, where the free-stream speed is sufficiently large that the vortex does not induce ejection of vorticity from the blade boundary layer prior to impact of the vortex core with the blade leading edge. A range of computations are performed for cases both with and without ambient axial flow in the vortex core. As the blade leading edge penetrates the vortex core, cross-diffusion between the columnar vortex and the blade boundary layer causes vortex lines originating in the columnar vortex to rapidly reconnect to those in the blade

boundary layer. This cutting process is found to be always incomplete however, due to a change in sign of the spanwise vortex-induced velocity along the leading edge as the vortex is cut, leaving a thin vortex sheet that wraps around the blade leading edge. Cutting of a vortex with non-zero axial flow causes an asymmetry that results in an impulsive lift force on the blade. This lift force has maximum magnitude during the time period where the blade leading edge penetrates the vortex core. Both the vortex cutting process and the unsteady lift force on the blade are found to be approximately independent of Reynolds number for the various cases examined.

Liu, X. and Marshall, J. S.

"AMPLIFICATION OF THREE-DIMENSIONAL PERTURBATIONS DURING PARALLEL VORTEX-CYLINDER INTERACTION"

J. Fluid Mech., Vol. 573, 2007, pp. 457-478

A computational study has been performed to examine the amplification of three-dimensional flow features as a vortex with small-amplitude helical perturbations impinges on a circular cylinder whose axis is parallel to the nominal vortex axis. For sufficiently weak vortices with sufficiently small core radius in an inviscid flow, three-dimensional perturbations on the vortex core are indefinitely amplified as the vortex wraps around the cylinder front surface. The paper focuses on the effect of viscosity in regulating amplification of three-dimensional disturbances and on assessing the ability of two-dimensional computations to accurately model parallel vortex-cylinder interaction problems. The computations are performed using a multi-block structured finite-volume method for an incompressible flow, with periodic boundary conditions along the cylinder axis. Growth of three-dimensional flow features is examined using a proper-orthogonal decomposition of the Fourier-transformed vorticity field in the azimuthal and axial directions. The interaction is examined for different axial wavelengths and amplitudes of the initial helical vortex waves and for three different Reynolds numbers.

Liu, X., Wu, S., Zhang, H., Wang, Q. and Zhai, X.

"COMPARISON OF WIND MEASUREMENTS BETWEEN VIRTUAL TOWER AND VAD METHODS WITH DIFFERENT ELEVATION ANGLES"

19th Coherent Laser Radar Conference (CLRC), Paper P32, June 2018, Okinawa, Japan.

This paper compares wind retrieval methods of VT (Virtual Tower) mode and VAD (Velocity-Azimuth Display) with different scanning elevation angles. The field experiment was performed from September 23 to October 13 2017 at the campus of Ocean University of China under various weather conditions. A total of seven lidars were involved in the experiment. Three lidars carried out the staring mode to constitute the VT. The other four lidars were concurrently operating PPI scanning at different elevation angles, corresponding to different spatial average volume. The results of wind speed and direction from VT and VAD shows good correlation when lidars are well synchronized. The influence of spatial homogeneity on wind retrieval is also described in this paper.

Liu, Y. and Sankar, L. N.

"COMPUTATIONAL EVALUATION OF CONTROLLING FLAP EDGE VORTEX AND TIP VORTEX EFFECTS WITH CIRCULATION CONTROL TECHNIQUE"

AIAA Paper No. 2007-473, Reno, NV, January 2007

This paper extends our previous work on the two-dimensional Circulation Control (CC) airfoil studies to three-dimensional applications so that the potential benefits of CC techniques on controlling vortex and reducing noise can be evaluated. Two numerical simulations have been done to identify the effects of CC techniques on controlling the flap edge vortex and the tip vortex. The first is a stream-wise tangential blowing on a wing-flap configuration. It is demonstrated that a gradually varied CC blowing can eliminate flap-edge vortex, thus reducing flap-edge noise. The second case involves a span-wise tangential blowing over a rectangular wing with a rounded wing tip. It is found that CC blowing cannot eliminate the tip vortex. However, it can control and modify the location of the tip vortex to increase the vertical clearances between the wing and the tip vortex, thus reducing the blade vortex interaction (BVI) and the BVI noise.

Liu, Y. and Stumpf, E.

"ESTIMATION OF VEHICLE-LEVEL FUEL BURN BENEFITS OF AIRCRAFT FORMATION FLIGHT"

Journal of Aircraft, Vol. 55, No. 2, March-April 2018, pp. 853-861.

The present paper investigates the overall aircraft-level impact of formation flight in terms of total drag savings and fuel consumption reductions. The current work is carried out because of an in-house multidisciplinary integrated conceptual aircraft design optimization framework. An aerodynamic method based on potential flow theory is first adapted for the induced drag estimation of aircraft in formation flight. By integrating the formation flight aerodynamic methodology into the in-house aircraft design and optimization platform, the potential drag reduction for arbitrary aircraft configurations in formation can be assessed. For specific flight missions, the fuel burn reduction can be further determined. Through comparing with other simulation and experimental results, the proposed formation flight aerodynamic methods in the present work show very good agreement. A case study on two medium-range passenger aircraft indicates that the trailing aircraft could achieve up to 60 percent induced drag reduction with optimal longitudinal, lateral, and vertical aircraft separations within formation. The fuel burn savings of the trailing aircraft are calculated to be up to 16 percent for specific payload and flight range combinations. A reserve fuel study shows that around 2 percent fuel burn savings would be eroded due to conservative fuel planning in formation flight.

Liu, Y. Z., Chen, H. P. and Koyama, H. S.

"LDA: AN EXPERIMENTAL WHOLE FIELD INVESTIGATION ON CONFINED ROTATING FLOW WITH AND WITHOUT VORTEX BREAKDOWN"

10th International Symposium on Applications of Laser Techniques in Fluid Mechanics, July 2000, Lisbon, Portugal.

Rich complicated flow problems present in rotating flow inside cylindrical container, secondary flows, vortex breakdown, to name a few. The experimental research on vortex breakdown in rotating flows has been limited to visualizations up to now, and there are few quantitative measurement results. For the rotating flow with vortex breakdown, there are sharp changes of velocity distribution, especially direction of the fluid motion. Therefore, large number of measurement points is necessary to make clear the flow. With high measurement precision and broad dynamics band, LDA is suitable for whole field investigation on complicated recirculating flow with and without breakdown. However, it is unfortunately a point-by-point method, which makes duration of experimental whole field investigation much long. For the confined rotating flow inside cylindrical container with a rotating top lid, the method of adjusting the rotating rate dependent on measured temperature to keep Reynolds number is presented here, as a solution to the appreciable viscosity dependence of the working fluid on temperature. It is experimentally testified that the method is convenient to be used, and can keep the flow pattern at the same Reynolds number with high precision for long time. An experimental whole field investigation on confined rotating flow inside cylindrical container via LDA is presented in the paper. For $H/R=1.51$, $Re=330, 520, 610, 790, 990, 1290$ and 2180 , the whole field velocity distribution in the meridional plane is obtained. The flow patterns with existence and disappearance of vortex breakdown are made clear.

Liu, Y., Wang, J., Liu, Z. and Bao, F.

"EXPERIMENTAL INVESTIGATION OF WAKE VORTEX IN A WATER TOWING TANK"

Proceedings of the SPIE, Vol. 8417, article 84172Y, October 2012.

Wake vortex behind an aircraft would introduce great hazard to the following aircraft and threaten to the flight safety. Generic model using two rectangular airfoils was employed for generating wake vortex system to investigate the method of wake vortex alleviation. The investigation was carried out in a water towing tank equipped with a Particle Image Velocimetry system. Characteristics of double-vortex flow were analyzed for selected cases, proving that the intensity of the vortex is reduced with respect to the interaction between the wake vortices. The study exhibited that the R-L instability was most effectively triggered with parameter combinations of $\alpha-1 = 10$ deg, $\alpha-2 = 8$ deg and $b = 50$ mm respectively. As a result, the circulation of the wake vortices was alleviated by nearly 40 percent accordingly.

Liu, Y., Wu, M., Zhu, J. J., Lawrence, D. A., Gutmark, E. J., Myatt, J. H. and May, C. A.

"REACTIVE FLOW CONTROL OF DELTA-WING VORTEX"

Journal of Aircraft, Vol. 45, No. 3, May-June 2008, pp. 880-892.

In this paper, the reactive flow control of delta-wing trailing-edge vortices using along-core pulse-width-modulation flow injection is presented. Leading-edge vortices on the upper surface of a delta

wing can augment lift. Manipulating breakdown points of leading-edge vortices can effectively change the delta wing's lift and drag and generate attitude-control torque. In this paper, a black-box dynamic model for active flow control of vortex breakdown points is identified from wind-tunnel data using a model scheduling method. Based on the identified model, a closed-loop active flow controller is developed. Simulation and real-time wind-tunnel test show that the closed-loop controller can effectively manipulate the upper surface pressure of the delta wing, which indicates that the closed-loop controller can effectively control vortex breakdown points.

Liu, Z.

"MODELING THE RADAR SIGNATURE OF RAINDROPS IN AIRCRAFT WAKE VORTICES"

PhD Thesis, May 2013, University of Toulouse, Toulouse, France.

In recent years, wake vortex monitoring in real time has emerged as one of the key challenges in air traffic control at landing and taking-off. In clear air, several experimental tests have demonstrated that Lidar is an effective sensor for wake vortex monitoring. In rainy weather, Lidar becomes blind and Radar is a candidate sensor to detect the motion of raindrops in wake vortices. Thus, investigation on radar monitoring of wake vortices in rainy weather is of both scientific and practical interests. This topic has been tackled through three successive steps. Firstly, the motion of raindrops in wake vortices has been modeled and simulated. The equation of motion has been derived and the methodology to compute the raindrops' trajectory and distribution in the flow induced by the wake vortices has been proposed. Secondly, two simulators have been developed for evaluating the radar signatures of raindrops in wake vortices. One simulator is based on the simulation of radar signal time series, by superposing the radar backscattered signal from each raindrop in the wake vortex region. The other one is based on the raindrops' number concentration and velocity distribution in wake vortices, enabling the computation of radar signatures much more efficiently. Those simulators have been used to reproduce experimental configurations and the comparison between measured and simulated signature has shown an interesting agreement at X and W band. Lastly, the interpretation of radar signatures of raindrops in wake vortices has been presented. Based on the computation of three spectral moments, the dependence of radar signatures on rain rate, vortex circulation and radar parameters has been studied for vortices generated by different aircraft types. A wake vortex detection method based on the analysis of Doppler spectrum width of raindrops has been proposed. Considering radar scanning under flight path, a methodology to estimate the wake vortex characteristics has been proposed. Preliminary simulation results have shown its effectiveness.

Liu, Z. and Barbaresco, F.

"DOPPLER INFORMATION GEOMETRY FOR WAKE TURBULENCE MONITORING"

Matrix Information Geometry, edited by F. Nielsen and R. Bhatia, 2013, Springer-Verlag Berlin Heidelberg, pp. 277-290.

A wake vortex detector based on Doppler entropy was described in this paper using the methods of information geometry, which bridges the gap between the probability distribution and geometric quantities. The radar statistical signal models are parameterized as points on a manifold of covariance matrices. The Doppler information geometry provides a quantitative assessment of Doppler spectrum of radar signals by introducing the definition of Doppler entropy. The radar experimental results of monitoring wake turbulence close to the airport were used to illustrate the effectiveness of the wake vortex detector based on Doppler entropy and the new developed algorithm based on GPU parallel computation have been proved to be much more efficient regarding the computation time. The radar detection technology of wake turbulence is a very challenging work which is quite different from the radar detection of other objects, the future work on the detection performance of wake turbulence based on Doppler entropy will be of great interest for radar community. On the other hand, as a kind of powerful computational tools, GPU computation will be largely applied to radar real time signal processing due to its relative low cost and high efficiency. Besides the work described in this paper, in the framework of information geometry, the future efforts and insights into geometric properties of radar statistical signals will surely bring forth results on the new trend of radar detection technology.

Liu, Z., Jeannin, N., Vincent, F. and Wang, X.

"MODELING THE RADAR SIGNATURE OF RAINDROPS IN AIRCRAFT WAKE VORTICES"

Journal of Atmospheric and Oceanic Technology, Vol. 30, 2013, pp. 470-484.

The present work is dedicated to the modeling and simulation of the radar signature of raindrops within wake vortices. This is achieved through the computation of the equation of raindrop motion within the wake vortex flow. Based on the inhomogeneous distribution of raindrops within wake vortices, the radar echo model is computed for raindrops in a given resolution cell. Simulated Doppler radar signatures of raindrops within wake vortices are shown to be a potential criterion for identifying wake vortex hazards in air traffic control. The dependence of the radar signature on various parameters, including the radial resolution and antenna elevation angle, is also analyzed.

Liu, Z., Jeannin, N., Vincent, F. and Wang, X.

"DEVELOPMENT OF A RADAR SIMULATOR FOR MONITORING WAKE VORTICES IN RAINY WEATHER"

Proceedings of 2011 IEEE CIE International Conf. on Radar, October 2011, Chengdu, China, pp. 284-287.

A simulator for the evaluation of the radar signature of raindrops within wake vortices is presented. Simulated Doppler spectrum of raindrops within vortices led to think that it could be a potential criterion for identifying wake vortex hazard in rainy weather.

Liu, Z., Russell, J. W., Sankar, L. N. and Hassan, A. A.

"A STUDY OF ROTOR TIP VORTEX STRUCTURE ALTERATION TECHNIQUES"

Journal of Aircraft, Vol. 38, No. 3, May-June 2001, pp. 473-477.

Numerical studies of the tip-vortex structure from a hovering rotor with blowing are presented, and compared with the tip-vortex structure from a clean rotor, and from a rotor using a passive trailing-edge tip device. A hybrid, Navier-Stokes potential flow method is used to model the flowfield. A scheme that is fifth-order accurate in space is used to accurately capture the tip vortices. Velocity and vorticity data in the core of the vortex are studied at various planes behind the blade leading edge. These data for the clean rotor are first compared with experimental results obtained for the same rotor. Previously published results for the tip-vortex structure from the same rotor employing a passive tip device are discussed next. Finally, results for a rotor blade with upper and lower surface blowing are presented. It is concluded that the tip-vortex strength may be modified through blowing. Blowing is found to be just as effective as a spoiler in altering the tip-vortex strength, but does not have the high drag and torque penalty associated with spoilers.

Liver, P. A.

"ROLL-UP OF A VORTEX SHEET TRAILING FROM A VORTEX GENERATOR"

Ph.D. Thesis, January 1987, Tennessee University, Knoxville, TN

The roll-up of a vortex sheet trailing from an airfoil type vortex generator was investigated through various analytical models. The effects of a finite size vortex sheet and the effects of viscosity on the vortex trajectory are included as important factors. The problem is treated as two-dimensional with the streamwise direction being replaced by the time coordinate assuming that the streamwise gradients are small compared to the development in the crossflow plane. The strength and the distribution of vorticity in the wake sheet trailing from the vortex generator are determined using a modified vortex lattice approach. The influence of the airfoil represented by its camber distribution and the effects of the velocity profile of the oncoming boundary layer are investigated. The effects of finite size of the initial vortex sheet and the associated finite formation rate of the trailing vortex are isolated by employing an inviscid vortex sheet roll-up calculation. Viscous effects on the vortex strength and on the trajectory are included by the application of the vorticity-stream function form of the Navier-Stokes equations.

Loaec, S., Thobois, L., Cariou, J.-P., Dolfi-Bouteyre, A. and Goular, D.

"MONITORING WAKE VORTICES WITH A SCANNING DOPPLER LIDAR"

9th International Symposium on Tropospheric Profiling (ISTP), September 2012, University of L'Aquila, L'Aquila, Italy.

Measuring and foreseeing wind conditions near airports are crucial issues for air traffic safety. Since aircraft maneuverability is the worst during takeoff and landing phases, strong air movements near airports such as wake vortices can have dramatic consequences on aircrafts. Wake vortices are created by all the aircrafts. Size and intensity of wake vortices are directly linked to the flight speed and also by plane characteristics, such as weight and wingspan. Even if strong efforts have been done to study and

model wake vortices, onsite measurements remain the best way to detect them as they depend a lot on meteorological conditions near airports especially wind and turbulence. Coherent laser radars or LIDARs can be very useful devices for monitoring wake vortices on airports. A WINDCUBE 200S developed by LEOSPHERE has been deployed at Charles De Gaulle airport near Paris in the framework of the European project SESAR and the subpackage 12.2.2 dedicated to wake vortices detection in cooperation with THALES AIR SYSTEMS. With specific swept scenarios, the WINDCUBE 200S has been able to detect the wake vortices of heavy, medium, and small aircrafts during takeoff and landing. Wake vortices have been monitored for a significant period. A dedicated post-treatment has been developed by the French Aerospace Lab ONERA for computing the cores position of wake vortices and for calculating their circulations. Thanks to that post-treatment the evolution of wake vortices trajectories and circulations can be determined. Several analyses have been achieved in order to determine the influence of the wind conditions on the trajectories of wake vortices. A variety of trajectories have been put in front.

Lobanova, M. A.

"A STUDY OF FLOW AND INITIAL STAGE OF WATER CONDENSATION IN THE TWO-PHASE JET-VORTEX WAKE BEHIND A CRUISE AIRCRAFT"

ICAS 2014, September 2014, St. Petersburg, Russia.

The paper describes the results of numerical investigation of large-scale flow structure in the near aircraft wake based on Reynolds Averaged Navier-Stokes equations. Influence of computational domain decomposition, grid refinement and the flow model on the jet flow field is analyzed. Initial growth of water clusters in the exhaust jet and the cluster distribution in size are studied at different distance from the nozzle outlet.

Lock, C. N. H., Hilton, W. F. and Goldstein, S.

"DETERMINATION OF PROFILE DRAG AT HIGH SPEEDS BY A PITOT TRAVERSE METHOD"

ARC-RM-1971, Ministry of Aircraft Production, Aeronautical Research Committee Reports and Memoranda, London, UK, September 1940.

At speeds at which the compressibility of the air can be neglected it is known that the profile drag of an airfoil section can be determined with sufficient accuracy from measurements of total head and static pressure across a section of the wake. For compressible flow, it appears that it is sufficiently accurate to assume that the total energy per unit mass of the air is constant, along with the measurements of total and static pressures. It is shown that the assumption of constant total energy is equivalent to assuming constant total stagnation temperature, and experimental evidence of this equivalence (up to Mach number 0.9, the available dataset used herein) has been obtained.

Lockard, D. P. and Morris, P. J.

"WING-TIP VORTEX CALCULATIONS USING A HIGH-ACCURACY SCHEME"

Journal of Aircraft, Vol. 35, No. 5, September-October 1998, pp. 728-738

The objective of the research described in this paper is to investigate the use of computational aero-acoustics methodology and parallel computers to simulate the development of a tip vortex. A three-dimensional Euler code, implemented using the message passing library and Fortran 90 on the IBM SP2, is used to perform calculations of the steady flow. Results are presented for low-speed flow over a finite span NACA 0012 wing. Comparisons with experimental data show that the tip vortex is predicted to diffuse too rapidly, but the high-accuracy scheme does reduce numerical errors. It is argued that Navier-Stokes calculations on a much finer mesh would improve the solutions, but they would be prohibitively expensive for unsteady calculations.

Lofthouse, A. J. and Buxton, N. W.

"CFD MODELING OF B-52 AND KC-135 IN AERIAL REFUELING FORMATION"

AIAA Paper 2017-4236, June 2017, Denver, CO.

This project investigated the potential for full-aircraft Computational Fluid Dynamics (CFD) simulation to replace flight testing to generate aerodynamic coefficients for use in a 6-Degree-of-Freedom ground-based flight simulator aerodynamics model. CFD was used to generate a dataset of aerodynamic coefficients for a B-52 in aerial refueling formation with a KC-135 tanker. Overset meshes were used for dynamic control surface deflections, and to place the B-52 and KC-135 at any angle-of-attack or angle-of-sideslip, with respect to each other, without requiring additional mesh generation. Results were largely in line with expectations; the greatest effect of the KC-135 was on the B-52 lift coefficient, due to the tanker downwash. No significant changes in control surface effectiveness were observed between the B-52 only and the B-52 / KC-135 formation. Simulations were also performed using near-body unstructured meshes overset on an off-body cartesian mesh to better resolve the tanker wake. While the project shows that it is feasible to simulate multiple aircraft in formation to extract the appropriate force and moment information for a flight simulator, further studies are required to determine if the tanker wake is fully resolved; to include tanker engine effects; and to determine changes in forces and moments as the relative position of the B-52 behind the KC-135 is changed.

Logan, A. H.

"VORTEX VELOCITY DISTRIBUTIONS AT LARGE DOWNSTREAM DISTANCES"

J. Aircraft, Vol. 8, No. 11, November 1971, pp. 930-932

This paper extends the available data on the velocity structure within a trailing line vortex to large distances downstream of the generating wing. Data are presented to show the variation of both axial and tangential velocity with tunnel speed and trailing vortex strength. Specifically, data are presented at downstream distances of 10 and 26 chord lengths behind a semispan wing at 4- and 12-degree angles of attack for tunnel speeds of 50 and 70 mph.

Logan, A. H.

"A SOLUTION TO THE VORTEX BREAKDOWN PHENOMENON IN A TRAILING LINE VORTEX"

M.S. Thesis, December 1966, Penn. State University, University Park, PA

A theoretical analysis of the vortex burst phenomenon in a trailing line vortex is carried out with the result being the development of a numerical solution to the line vortex behind a lifting surface. The acceleration or retardation of the axial velocity in a vortex in general was also predicted and supported by previous investigations and the present experimental work. Finally, both criteria for predicting vortex breakdown and a numerical program predicting the axial velocity deficit in the wake are developed theoretically and supported by experimental investigation.

Logory, L. M., Hirs, A. and Anthony, D. G.

"INTERACTION OF WAKE TURBULENCE WITH A FREE SURFACE"

Physics of Fluids, Vol. 8, Issue 3, 1996, pp. 805-815.

The turbulent wake of a flat plate aligned with a uniform water flow and extending through the free surface was investigated experimentally. Laser-Doppler velocimetry (LDV) measurements show good agreement with published data for a two-dimensional wake, except in a shallow layer near the free surface. In this surface layer, the wake width is observed to double while the wake centerline velocity remains essentially unchanged from its value at depth, resulting in a wake momentum deficit that is twice that at depth. Instantaneous, full-field measurements of the velocity were made using digital particle image velocimetry (DPIV) to elucidate the role of vortical structures in the development of the surface layer. DPIV measurements reveal that in the deep wake, vortex structures predominantly of opposite sign exist on opposite sides of the wake centerline and contribute to a velocity and vorticity field that is two-dimensional in the mean. However, near the surface, vortex structures tend to become either surface-normal or surface-parallel and contribute to a velocity and vorticity field that is highly three-dimensional in the mean. The resulting surface layer is characterized by surface-parallel structures interacting with their images above the surface to retard and widen the surface flow to a depth comparable to the size of the vortex structures. Histograms taken from many independent DPIV realizations of the flow characterize the distribution of vorticity in the wake and verify a mean flow consistent with the LDV measurements. The existence of these structures in the surface layer is further confirmed by flow visualization using laser-induced fluorescence.

Lohr, G. W., Williams, D. M., Trujillo, A. C., Johnson, E. J. and Domino, D. A.

"INFORMATION REQUIREMENTS FOR SUPERVISORY AIR TRAFFIC CONTROLLERS IN SUPPORT OF A MID-TERM WAKE VORTEX DEPARTURE SYSTEM"

NASA/TM-2008-215114, Feb. 2008, Langley Research Center, Hampton, VA

Closely Spaced Parallel Runway configurations are capacity limited for departures due to the requirement to apply wake vortex separation standards from traffic departing on the adjacent parallel runway. To mitigate the effects of this constraint, a concept focusing on wind dependent departure operations has been developed known as the Wake Turbulence Mitigation for Departures (WTMD). This concept takes advantage of the fact that crosswinds of sufficient velocity blow wakes generated by aircraft departing from the downwind runway away from the upwind runway. Consequently, under certain conditions, wake separations on the upwind runway would not be required based on wakes generated by aircraft on the downwind runway as is currently the case. It follows that information requirements, and sources for this information, would need to be determined for airport traffic control tower (ATCT) supervisory personnel who would be charged with decisions regarding the use of the procedure. To determine the information requirements, data were collected from ATCT supervisors and controller-in-charge qualified individuals at Lambert-St. Louis International Airport (STL) and George Bush Houston Intercontinental Airport (IAH). STL and IAH were chosen as data collection sites based on the implementation of a WTMD prototype system, operating in shadow mode, at these locations. The 17 total subjects represented a broad-base of air traffic experience. Results indicated that the following information was required to support the conduct of WTMD operations: current and forecast weather information, current and forecast traffic demand, traffic flow restrictions, and WTMD System status information and alerting. Subjects further indicated that the requisite information is currently available in the tower cab except for the WTMD status and alerting. Subjects were given a demonstration of a display supporting the prototype systems and unanimously stated that the WTMD status information they felt important was represented. Overwhelmingly, subjects felt that approving, monitoring, and terminating the WTMD procedure could be integrated into their supervisory workload.

Lohr, G., Williams, D. and Trujillo, A.

"INFORMATION REQUIREMENTS FOR SUPERVISORY AIR TRAFFIC CONTROLLERS IN SUPPORT OF A WAKE VORTEX DEPARTURE SYSTEM"

ICAS 2008, Anchorage, AK, Sept. 2008

Closely Spaced Parallel Runway configurations are capacity limited for departures due to the requirement to apply wake vortex separation standards from traffic departing on the adjacent parallel runway. To mitigate the effects of this constraint, a concept focusing on wind dependent departure operations has been developed, known as the Wake Turbulence Mitigation for Departures (WTMD). This concept takes advantage of the fact that crosswinds of sufficient velocity blow wakes generated by aircraft departing from the downwind runway away from the upwind runway. It follows that information requirements, and sources for this information, would need to be determined for airport traffic control tower (ATCT) supervisory personnel who would be charged with decisions regarding use of the procedure. Results indicated that the following information was required to support the conduct of WTMD operations: current and forecast weather information, current and forecast traffic demand, traffic flow restrictions, and WTMD System status information and alerting.

Lomax, H.

"LIFT DEVELOPED ON UNRESTRAINED RECTANGULAR WINGS ENTERING GUSTS AT SUBSONIC AND SUPERSONIC SPEEDS"

NACA Technical Note 2925, April 1953, Ames Aeronautical Laboratory, Moffett Field, CA.

The object of this report is to provide an estimate, based on theoretical calculations, of the forces induced on a wing that is flying at a constant forward speed and suddenly enters a vertical gust. The calculations illustrate the effects of Mach number (from 0 to 2) and aspect ratio (2 to infinity), and solutions are given by means of which the response to gusts having arbitrary distributions of velocity can be calculated. The effects of pitching and wing bending are neglected and only wings of rectangular plan form are considered. Specific results are presented for sharp-edged and triangular gusts and various wing-air density ratios.

Lomax, H. and Sluder, L.

"DOWNWASH IN THE VERTICAL AND HORIZONTAL PLANES OF SYMMETRY BEHIND A TRIANGULAR WING IN SUPERSONIC FLOW"

NACA Technical Note No. 1803, January 1949, Ames Aeronautical Lab., Moffett Field, CA.

A method developed in a previous report for finding the induced velocity field behind a supersonic wing with known load distribution is used to find the downwash behind a triangular wing with subsonic leading edges. Results are given for the chord plane in the extended vortex wake of the wing and for the vertical plane of symmetry up to about 20 percent of the wing span above the plane of the wing.

Lombard, J.-E. W., Moxey, D., Sherwin, S. J., Hoessler, J. F. A., Dhandapani, S. and Taylor, M. J.

"IMPLICIT LARGE-EDDY SIMULATION OF A WINGTIP VORTEX"

AIAA Journal, Vol. 54, No. 2, February 2016, pp. 506-518.

In this article, recent developments in numerical methods for performing a large-eddy simulation of the formation and evolution of a wingtip vortex are presented. The development of these vortices in the near wake, in combination with the large Reynolds numbers present in these cases, makes these types of test cases particularly challenging to investigate numerically. First, an overview is given of the spectral vanishing viscosity/implicit large-eddy simulation solver that is used to perform the simulations, and techniques are highlighted that have been adopted to solve various numerical issues that arise when studying such cases. To demonstrate the method's viability, results are presented from numerical simulations of flow over a NACA 0012 profile wingtip at $Re = 1,200,000$ and they are compared against experimental data, which is to date the highest Reynolds number achieved for a large-eddy simulation that has been correlated with experiments for this test case. The model in this paper correlates favorably with experiment, both for the characteristic jetting in the primary vortex and pressure distribution on the wing surface. The proposed method is of general interest for the modeling of transitioning vortex-dominated flows over complex geometries.

Lombardi, G. and Cannizzo, F.

"HIGH ASPECT RATIO WINGS - TIP VORTEX STRUCTURE AND ITS NUMERICAL IMPLICATIONS"

AIAA Paper No. 1996-1961, New Orleans, LA, June 1996

Some aspects related to the evaluation of the loads on high aspect ratio wings are analyzed. The complex structure of the flow typology close to the tip vortex is first studied by experiment. The formation of the tip vortex was found to take place by a complex mechanism. Subsequently, to verify the capability of different types of numerical codes to describe the effects of this type of flow, a comparison between numerical and experimental results is carried out considering the pressure distributions acting on sections close to the wing tip of an unswept and a forward-swept wing. Different non-viscous methods, typically used for the evaluation of lift distribution along the wing span, are shown to give rise to significant errors in the load evaluation close to the wing tip, due to the impossibility of adequately representing the tip flow typology. In particular, the lift close to the wing tip tends to be underestimated by a potential panel method and overestimated by an Euler code. Although these discrepancies are limited to a small zone close to the wing tip, they could produce non-negligible errors in the wing root bending moment.

Lombardi, G. and Skinner, P.

"WING-TIP VORTEX IN THE NEAR FIELD: AN EXPERIMENTAL STUDY"

J. of Aircraft, Vol. 42, No. 5, September-October 2005, pp. 1366-1368

An experimental study of the initial formation of the wing-tip vortex was conducted. The vorticity was directly measured using a vorticity probe, whose experimental uncertainties are smaller than those of other measurement probes. The measurements document, over a small streamwise distance, the formation of a double-core vortex structure that subsequently merges into a single vortex. The spanwise position of the primary vortex core varies as the square root of the streamwise distance; this is in good agreement with previous studies.

Lombardi, G., Talamelli, A. and Sjoberg, J.

"VORTICITY MEASUREMENTS IN THE NEAR-FIELD OF A WING TIP VORTEX"

ICAS Paper 98-3.2.2, Sept. 1998, Melbourne, Australia.

The initial phase of the roll-up of the wing tip vortex, emanating from high aspect ratio wings, is considered. An experimental investigation, based on hot-wire anemometry technique, is in progress; the measurement procedures used and some of the preliminary results are described. Tests are carried out on a tapered, no-swept wing model, with aspect ratio 5.7. The statistically averaged quantities of interest, viz. the three mean velocity components, the whole Reynolds stress tensor and the third order moments tensor, are measured, by combining different responses of the wires of single or X-wire probes positioned at different orientations in the measurement points. This procedure avoids the difficulties connected with the use and calibration of triple-wire probes and permits the use of

considerably smaller and less intrusive probe. A continuous complex wavelet transform technique is also used to assess some characteristics of the tip vortex wandering. Furthermore, to verify the results, a different measurement procedure, based on a pressure vorticity meter, has been used; it allows the time history of quantities related to the streamwise component of the vorticity to be obtained.

Loney, M. R. and Goldberg, D. F.

"THE BENEFITS OF REDUCED SEPARATION STANDARDS AT CHICAGO O'HARE INTERNATIONAL AIRPORT"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 29-1 - 29-14

In this paper, data collected for the Chicago Delay Task Force Study serve as the basis for an assessment of the operational benefits of reduced wake-vortex separation at Chicago O'Hare International Airport, using AIRSIM, an FAA approved airspace/airfield simulation model. Existing wake-vortex separation standards are simulated as the baseline scenario, while the aircraft separation research goals defined in the FAA Wake Vortex Research Program Plan are simulated as the test-case scenario. The operational benefits of reduced wake-vortex separation standards are defined as the difference in aircraft operational delays incurred under the test-case scenario relative to the performance of the baseline scenario. In addition, the effect on delay of changes in operating factors, such as fleet mix and meteorological conditions, is examined with respect to reduced separation standards. This assessment demonstrates the ability to reduce annual delays at O'Hare by more than 10,000 hours with reduced wake-vortex separation standards, reflecting a direct airline operating cost savings of \$20 million per year. In addition, the analysis suggests that the expected delay reduction increases: 1) as the percentage of 'Heavy' (i.e., 300,000 pounds or greater) aircraft increases; 2) as the level of ATC coordination decreases; and 3) as the level of demand approaches airport capacity.

Lonfils, T., Daeninck, G. and Winckelmans, G.

"3D FILAMENT SIMULATIONS OF CROW-LIKE INSTABILITIES IN GROUND EFFECT"

AST4-CT-2005-012238, Universite Catholique de Louvain, Louvain-la-Neuve, Belgium, September 2006

The purpose of this work is to investigate two vortex systems in ground effect (IGE) using a vortex filament method. The method being inviscid, the scope of this study is however reduced: 2-D and 3-D (DNS and LES) results clearly show that a very important effect for wake vortices (WV) IGE is the viscous interaction with the ground through the creation of secondary vortices. We therefore restrict the study to the analysis of long wave (Crow-type) instabilities for WV IGE. After briefly describing the numerical method, we investigate two cases: (i) a configuration as close as possible to the one studied experimentally by CNRS-IRPHE (i.e., a thick vortex pair IGE with a forced long wave instability) and (ii) the case of aircraft like vortices IGE with a forced Crow instability (at different initial perturbation levels).

Long, K.

"INVESTIGATIONS OF SHIPBOARD ROTORCRAFT INTERACTIONAL AERODYNAMICS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Since 1943, the US Navy has conducted Dynamic Interface (DI) shipboard flight tests to evaluate all aspects of shipboard rotorcraft compatibility, and to develop shipboard rotorcraft operating envelopes. The shipboard environment poses unique challenges to routine fleet operations and test operations alike. Since the mid-1990s, the US Navy has increasingly focused on developing improved analytic techniques that would facilitate more efficient and cost-effective shipboard rotorcraft flight test programs. This paper summarizes recent USN investigations, which include wind tunnel, CFD and other analytic efforts, conducted at NASA Ames Research Center, which are designed to investigate shipboard rotorcraft interactional aerodynamics, thereby allowing the USN to optimize and improve shipboard rotorcraft compatibility. The paper and accompanying brief summarize a variety of wind tunnel efforts, which were conducted to investigate and characterize the complicated flow fields that exist aboard various USN ship classes, for use in improving USN shipboard flight test programs. The efforts included investigations of the wake flow around simplified and complicated three-dimensional ship structures, with and without model rotorcraft (both conventional and tiltrotor) imposed into the flow. These investigations included a variety of quantitative and qualitative measurement techniques, including surface oil and wake smoke flow visualization, a seven-hole probe, hot wire anemometry, particle image velocimetry surface pressure taps, pressure sensitive paint, and shear-sensitive liquid crystals. The wind tunnel results are compared with calculations and with full-scale shipboard flight test data.

Long, L. N.

"RECENT ADVANCES IN COMPUTING AND VISUALIZATION RELEVANT TO AIRPORT CAPACITY"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

To keep the number of new airports and runways to a minimum, there is an urgent need to increase their efficiency while reducing the aircraft accident rate. This paper will describe several roles that computing and visualization can play in helping to meet future airport capacity issues. In particular, runway independent aircraft (primarily rotorcraft) promise to ease congestion by moving passengers through the airports without utilizing traditional runways. It will be essential to use computers to help design future rotorcraft that are quiet, efficient, cost effective, and reliable. In addition, computer visualization will be very valuable in future air traffic control systems. One of our research efforts attempts to create a general software system to integrate Virtual Reality with real-time numerical simulations for visualizing aircraft wakes near and around airports. Specifically, this work aims at creating a wake-vortex hazard avoidance system by realistically simulating an airport with real-time visualization of the predicted wake-vortices generated by the moving aircraft. The dangers (and unknowns) associated with aircraft flying through wake-vortices is a dominant limiting factor in airport throughput. If implemented, such a system has the potential to greatly increase the utilization of

airports while reducing the risks of possible accidents. Since the wake-vortex prediction for an entire fleet of aircraft taking-off and landing at a busy airport is a computationally intensive problem, a parallel solution is proposed.

Long, R. R.

"A VORTEX IN AN INFINITE VISCOUS FLUID"

J. Fluid Mech., Vol. 11, Part 4, December 1961, pp. 611-624

A solution is given for a viscous vortex in an infinite liquid. Similarity arguments lead to a reduction of the equations of motion to a set of ordinary differential equations. These are integrated numerically. A uniform feature is the constant circulation K outside the vortex core, which is also a viscous boundary layer. The circulation decreases monotonically towards the axis. The axial velocity profiles and the radial velocity profiles have several characteristic shapes, depending on the value of the non-dimensional momentum transfer M . The solution has a singular point on the axis of the vortex. The radius of the core increases linearly with distance along the axis from the singularity, and, at a given distance, is proportional to the coefficient of viscosity and inversely proportional to K .

Long, R. R.

"VORTEX MOTION IN A VISCOUS FLUID"

J. of Meteorology, Vol. 15, Issue 1, Feb. 1958, pp. 108-112

A discussion is given of a three-dimensional vortex in a viscous fluid. A theory is outlined that leads to a reduction of the steady-state Navier-Stokes equations of an incompressible fluid to three ordinary, nonlinear, differential equations. Although no numerical results are available, qualitative arguments based on these equations and on the form of their dependent and independent variables throw considerable light on the structure of the vortex. One important result is that the vertical velocity is of the same order of magnitude as the horizontal velocity.

Longo, J. M. A., Orlowski, M. and Strohmeyer, D.

"FLOWFIELD OF A WING EMBEDDED IN THE WAKE OF A BURSTED VORTEX"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 16-1 to 16-8

In the present paper the flowfield around a delta wing partially embedded in the wake of a burst vortex is numerically studied at $M\text{-}\theta=0.4$. The simulation is carried out solving the Euler equations on two structured grids of about 2.3 million points and 300000 points respectively. Due to the lack of experimental results, special emphasis is put on the analysis of the effect of grid fineness on the wake-flow. The present investigation indicates that the spiraling flow of a vortex continues after breakdown

with a swirl velocity comparable to that of a non-bursted vortex generated at lower angles of attack and hence interference effects coming from its wake persist long downstream.

Lopez, J. M.

"AXISYMMETRIC VORTEX BREAKDOWN, PART 1, CONFINED SWIRLING FLOW"

Journal of Fluid Mechanics, Vol. 221, 1990, pp. 533-552.

A comparison between the experimental visualization and numerical simulations of the occurrence of vortex breakdown in laminar swirling flows produced by a rotating end wall is presented. The experimental visualizations of Escudier were the first to detect the presence of multiple recirculation zones and the numerical model presented here, consisting of a numerical solution of the unsteady axisymmetric Navier-Stokes equations, faithfully reproduces these phenomena and all other observed characteristics of the flow. Further, the numerical calculations elucidate the onset of oscillatory flow, an aspect of the flow that was not clearly resolved by the flow visualization experiments. Part 2 of the paper examines the underlying physics of these vortex flows.

Lopez, J. M. and Perry, A. D.

"AXISYMMETRIC VORTEX BREAKDOWN, PART 3, ONSET OF PERIODIC FLOW AND CHAOTIC ADVECTION"

Journal of Fluid Mechanics, Vol. 234, 1992, pp. 449-471.

When the fluid inside a completely filled cylinder is set in motion by the rotation of one endwall, steady and unsteady axisymmetric vortex breakdown is possible. Nonlinear dynamical systems theory is used to describe the changing kinematics of the flow as the speed of the rotating endwall is increased. Two distinct modes of oscillation have been found in the unsteady regime and the chaotic advection caused by the oscillations has been investigated. The results of this study are used to describe the filling and emptying processes of the vortex breakdown bubbles observed in flow visualization experiments.

Lopez, J. M., Cui, Y. D., Marques, F. and Lim, T. T.

"QUENCHING OF VORTEX BREAKDOWN OSCILLATIONS VIA HARMONIC MODULATION"

J. Fluid Mech., Vol. 599, 2008, pp. 441-464

Vortex breakdown is a phenomenon inherent to many practical problems, such as leading-edge vortices on aircraft, atmospheric tornadoes, and flame-holders in combustion devices. The breakdown of these vortices is associated with the stagnation of the axial velocity on the vortex axis and the development of a near-axis recirculation zone. For large enough Reynolds number, the breakdown can be time-dependent. Here we present results from a combined experimental and numerical investigation of vortex breakdown in an enclosed cylinder in which low-amplitude modulations of the rotating end wall that sets up the vortex are used as an open-loop control. As expected, for very low amplitudes of the modulation, variation of the modulation frequency reveals typical resonance tongues

and frequency locking, so that the open-loop control allows us to drive the unsteady vortex breakdown to a prescribed periodicity within the resonance regions. For modulation amplitudes above a critical level that depends on the modulation frequency (but still very low), the result is a periodic state synchronous with the forcing frequency over an extensive range of forcing frequencies. Of particular interest is the spatial form of this forced periodic state: for modulation frequencies less than about twice the natural frequency of the unsteady breakdown, the oscillations of the near-axis recirculation zone are amplified, whereas for modulation frequencies larger than about twice the natural frequency the oscillations of the recirculation zone are quenched, and the near-axis flow is driven to the steady axisymmetric state.

Lord, R. J., Menzel, W. P. and Pecht, L. E.

"ACARS WIND MEASUREMENTS: AN INTERCOMPARISON WITH RADIOSONDE, CLOUD MOTION AND VAS THERMALLY DERIVED WINDS"

Journal of Atmospheric and Oceanic Technology, Vol. 1, 1984, pp. 131-137.

Statistical comparisons between winds measured by ACARS and winds obtained from radiosondes, geostationary satellite image cloud motions, and VAS are presented. Observations from three separate comparisons reveal over 60 percent of wind vector magnitude differences are within 9 m/s, and 70 percent of the directional differences are within 15 degrees. The comparisons indicate that the ACARS system provides an independent source of wind data that complements other sources of wind data for constructing composite wind field analyses.

Loth, J. L.

"WIND POWER LIMITATIONS ASSOCIATED WITH VORTICES"

AIAA Paper 1978-0278, January 1978, Huntsville, AL.

The total pressure dissipation inside vortices, due to viscous shear, has been analyzed. The reduced level of the total pressure flux, of the flow inside a vortex, has an adverse effect on all vortex ingesting wind machines. The Betz limit of wind turbines ingesting the vortex generated by an airfoil has been computed and is non-dimensionalized using the area of the vortex generator. The vacuum pumping ability of vortices is also limited. The Betz type limit for wind turbines exhausting into the core of a vortex has been computed for both wing tip and tornado tower type vortex generators. The energy required to eliminate a tornado has been computed.

Lott, J. N., Vose, R. S., Del Greco, S. A., Ross, T. R., Worley, S. and Comeaux, J. L.

"THE INTEGRATED SURFACE DATABASE: PARTNERSHIPS AND PROGRESS"

24th AMS Conference on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology (IIPS), Paper 131387, Jan 2008, New Orleans, LA.

The National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) is responsible for the stewardship of global climatological data to support a variety of applications in the private, research, and public sectors. This includes the development of datasets to be used as input for a planned global climatological reanalysis. In support of these activities and to better streamline operations, NCDC implemented a plan to integrate surface climatological data into a common format and data model and process these data through one processing system that capitalizes on network-independent standardized quality control algorithms and procedures. Federal Climate Complex (FCC) partners (US Air Force and Navy) collaborated closely with NCDC in development of the global Integrated Surface Database (ISD), providing large volumes of data as input sources. Now, through additional partnerships, ISD is being further expanded and enhanced.

Lott, N., Baldwin, R. and Jones, P.

"THE FCC INTEGRATED SURFACE HOURLY DATABASE, A NEW RESOURCE OF GLOBAL CLIMATE DATA"

NOAA Technical Report No. 2001-01, November 2001, National Climatic Data Center, Asheville, NC.

As a result of Environmental Services Data and Information Management (ESDIM) funding, Office of Global Programs (OGP) funding, and extensive contributions from member agencies in the Federal Climate Complex (FCC), the National Climatic Data Center (NCDC) has completed two phases of the Integrated Surface Hourly (ISH) database project.

Loucel, R. E. and Crouch, J. D.

"FLIGHT-SIMULATOR STUDY OF AIRPLANE ENCOUNTERS WITH PERTURBED TRAILING VORTICES"

Journal of Aircraft, Vol. 42, No. 4, July-August 2005, pp. 924-931

This study provides a preliminary, but concrete, assessment of the potential benefits of causing the breakup of airplane trailing vortices via large-scale instability, resulting in vortex rings. The 737-300 flight simulator is used to model the autopiloted response of an airplane encountering the vortices at different stages in the breakup process. A series of encounters with straight vortices is used to establish a baseline response. For the early stages of the vortex breakup, the vortices are modeled as wavy vortex filaments. For the late stages of the vortex breakup, the vortices are modeled as vortex rings, whose shape is based on experimental observation. The primary results of the study are presented in a collection of contour plots for the maximum bank angle that occurs during an encounter. The bank angles are given as a function of the horizontal and vertical vortex-intercept angles. The results show a significant reduction in the maximum bank angle, experienced by the encountering airplane, because of the vortex breakup. The simulations show a continuous reduction in the level of

upset as the vortices become increasingly wavy and ultimately break up into rings. The most significant reductions (both in terms of the magnitudes of the upset and the likelihood of their occurrence) result from the formation of vortex rings. The results suggest that the controlled breakup of the vortices could be exploited to enable reduced airplane separations, based on a vortex-destruction concept in addition to vortex avoidance.

Louf, V., Protat, A., Jackson, R. C., Collis, S. M. and Helmus J.

"UNRAVEL: A ROBUST MODULAR VELOCITY DEALIASING TECHNIQUE FOR DOPPLER RADAR"

Journal of Atmospheric and Oceanic Technology, Vol. 37, May 2020, pp. 741-758.

Unfold Radar Velocity (UNRAVEL) is an open-source modular Doppler velocity de-aliasing algorithm for weather radars. UNRAVEL is an algorithm that does not need external reference velocity data, making it easily applicable. The proposed algorithm includes 11 core modules and 2 de-aliasing strategies. UNRAVEL is an iterative algorithm. The goal is to build the de-aliasing results starting with the strictest possible continuity tests in azimuth and range and, after each step, relaxing the parameters to include more results from a progressively growing number of reference points. UNRAVEL also has modules that perform 3D continuity checks. Thanks to this modular design, the number of de-aliasing strategies can be expanded in order to optimize the de-aliasing results. While the first driver de-aliases Doppler velocity from each tilt independently from one another, the second driver also performs a three-dimensional continuity check of the velocity using successive elevations. The proposed de-aliasing algorithm is tested using severe weather data from an S-band Doppler radar that have been aliased to mimic aliased radial velocity patterns that would be observed by a C-band Doppler radar. Artificially aliasing S-band data permits creation of a reference to which the performance of various de-aliasing techniques can be compared. Comparisons show that UNRAVEL consistently outperforms other established de-aliasing algorithms for the test period selected in this work.

Lovell, D. A.

"MILITARY VORTICES"

RTO AVT Symposium on Advanced Flow Management, May 2001, Loen, Norway.

This paper briefly reviews the wide range of vortex flows encountered on military vehicles. Vortex flows are classified into those designed into a vehicle to improve performance, those which cannot be avoided and whose deleterious effects must be minimized, and those that were not expected to occur. Examples of vortex-flow effects on air and sea vehicles and in propulsion systems are cited to illustrate these categories. It is concluded that vortex flows are all-pervasive and can have major effects on the operation and performance of military vehicles. With the trend to increased diversity in shape for future vehicles it is deemed essential to continue to improve the knowledge and predictive capability for vortex flows.

Lowe, J. D.

"CALCULATION OF LIFT-CURVE SLOPE USING A WING TIP BIASED VORTEX DISTRIBUTION"

J. Aircraft, Vol. 25, No. 5, May 1988, pp. 472-473

A horseshoe vortex model based on wing tip biased cascades of vortices modifying a central vortex core has been used to calculate the lift-curve slope of a flat, untwisted rectangular wing. If the cascades are confined to the outer quarters of the wing, the lift-curve slope can be calculated to a reasonable degree of accuracy over a broad range of aspect ratios using seven vortex elements. At very high aspect ratios greater than 30, limiting the wing tip cascades to the outermost $1/AR$ fractions of the wing improves the accuracy of the calculations. This provides a method of calculating aerodynamic properties that is not computation intensive while at the same time attempting to model the more qualitative properties of the flow. Conventional horseshoe vortex methods based on extended lifting-line theory can be modified to model the rapid changes in flow properties near the wing tips by using nonuniform distributions of vorticity. One such technique is the so-called 'circle distribution method' whereby a semicircle, whose diameter is the quarter-chord line, is erected over the wing and equally spaced arcs are projected onto the quarter-chord line to form the bound vortex segments. As a result, the horseshoe vortices are more densely packed near the tips than in the center of the wing. However, the concept of the whole wing as a composite of many smaller wings is not changed from the uniform distribution method; only the distribution of vorticity has changed. The main difference between the wing tip biased method and other methods is in its perception of the wing as a simple horseshoe-shaped vortex structure that is explicitly modified by its tips.

Lowry, J. G. and Polhamus, E. C.

"A METHOD FOR PREDICTING LIFT INCREMENTS DUE TO FLAP DEFLECTION AT LOW ANGLES OF ATTACK IN INCOMPRESSIBLE FLOW"

NACA Technical Note 3911, January 1957, Langley Aeronautical Laboratory, Langley Field, VA.

A method is presented for estimating the lift due to flap deflection at low angles of attack in incompressible flow. In this method provision is made for the use of incremental section-lift data for estimating the effectiveness of high-lift flaps. The method is applicable to swept wings of any aspect ratio or taper ratio. The present method differs from other current methods mainly in its ease of application and its more general application. Also included is a simplified method of estimating the lift-curve slope throughout the subsonic speed range.

Lowson, M. V.

"VISUALIZATION MEASUREMENTS OF VORTEX FLOWS"

J. Aircraft, Vol. 28, No. 5, May 1991, pp. 320-327

Novel flow visualization experiments have been used on the separated vortex flow on a delta wing at low speed to give measurements of flow parameters for comparison with theory. Data on vortex core

position, vortex sheet shape, vortex strength, and local velocity magnitude and direction in the core have been determined. The results show surprising consistency with several features of established theoretical models for high Re flows and further justify the use of low Re experiments for vortex flows. The results also indicate areas where care should be taken in extrapolating results at low Re to flight cases.

Lu, T.

"ON THE DYNAMICS OF VORTEX FILAMENTS AND THEIR CORE STRUCTURE"

Journal of Shanghai University, Vol. 3, No. 2, June 1999, pp. 87-94.

We give a brief review of the asymptotic theory of slender vortex filaments with emphasis on (i) the choices of scaling and small parameters characterizing the physical problem, (ii) the key steps in the formulation of the theory and (iii) the assumptions and/or restrictions on the theory of Callegari and Ting (1978). We present highlights of an extension of the 1978 asymptotic theory: the analyses for core structures with axial variation. Making use of the physical insights gained from the analyses, we present a new derivation of the evolution equations for the core structure. The new one is simpler and straightforward and shows the physics clearly.

Lu, W., Zhao, Q. and Xu, G.

"ANALYSIS OF ROTOR WAKE STABILITY IN FORWARD FLIGHT ASSOCIATED WITH DISTORTION REVISE"

Acta Aeronautica et Astronautica Sinica, Vol. 33, No. 11, November 2012, pp. 1958-1966.

The state of the art in the analysis of rotor wake stability has its limitation that it will obtain impractically large divergence rate where the vortex filaments get too close. To eliminate this unreasonable interference in the analysis of rotor wake stability coming from highly distorted wakes in forward flight, a linearized method of wake stability analysis associated with wake distortion revision under a sinusoidal perturbation is presented. In this method, the wake vortex filaments are discretized into a series of vortex elements with a sinusoidal perturbation distributed on the nodes along the vortex filaments, where the self/mutually-induced velocity of wakes and the influence of blades is considered. A fake vortex core is novelly applied to revise this unreasonable interference in the analysis of rotor wake stability coming from highly distorted wakes. Taking the H-34 model rotor as a numerical example, the influence of wake drifting, size of vortex core and advance speed on rotor wake stability are calculated by this method and analyzed individually in forward flight. The results show that the fake vortex core can effectively revise the impractically large divergence rate where the vortex filaments are getting too close. Furthermore, in forward flight, the change of the size of vortex core or advance speed, etc., cannot change the inherent instability of rotor wakes, but it can slightly influence the instabilities under some conditions. [In Chinese.]

Lu, Z.

"MERGE OF A VORTEX-PAIR"

AIAA Paper No. 2004-2419, Portland, OR, June-July 2004

The unsteady merging process of two identical circular vortex cores is further studied using the diffusing-vortex method. A series of new results for vorticity field and instantaneous stream line patterns are presented. The accuracy of the numerical results is analyzed and examined in terms of the initial invariants and decay laws of vorticity distribution.

Lua, K. B., Lim, T. T., Yeo, K. S. and Oo, G. Y.

"A STUDY OF WAKE STRUCTURES OF A HEAVING TWO-DIMENSIONAL ELLIPTIC AIRFOIL USING DPIV TECHNIQUE"

AIAA Paper No. 2007-276, Reno, NV, January 2007

The formation of the wake structures of a two-dimensional (2D) elliptic airfoil executing a simple harmonic heaving motion is investigated using Digital Particle Image Velocimetry (DPIV) technique. This work is motivated partly by the lack of experimental data on a 2D heaving elliptic airfoil and partly by the anomaly between the numerical results of Lewing and Haz-Hariri [Lewin, G. C. and Haj-Hariri, H., 'Modelling thrust generation of a two-dimensional heaving airfoil in viscous flow, ' Journal of Fluid Mechanics, Vol. 492, 2003, pp. 339-362] and dye visualization results of Lai and Platzer [Lai, J. C. S and Platzer, M. F., 'Jet Characteristics of a Plunging Airfoil', AIAA Journal, Vol. 37, No. 12, 1999, pp. 1529-1537]. The former study found that both the leading-edge vortices (LEV) and the trailing edge vortices (TEV) contributed to the formation of the wake structures of a 2D heaving elliptic airfoil, whereas the latter study showed that only the TEV contributed to the wake structures of a heaving NACA 0012 airfoil. Possible reasons for the anomaly are provided.

Luber, W.

"WAKE PENETRATION EFFECTS ON DYNAMIC LOADS AND STRUCTURAL DESIGN OF MILITARY AND CIVIL AIRCRAFT"

Proceedings of the IMAC-XXVIII, Society for Experimental Mechanics, Feb. 2010, Jacksonville, FL, pp. 1381-1402.

The effects on the structural design of military and civil aircraft caused by dynamic loads resulting from the flight through high wake velocities which are generated by different types of aircraft have not been sufficiently investigated in the past. Military aircraft might experience this impact during formation or squadron flight or during combat maneuvers. Civil aircraft could be affected during start and cruise through wakes from other aircraft. Passing through the wake the safety of the aircraft might be critical by wrong guidance, uncontrolled movements or by induced dynamic loads which might cause failure of structure or structural fatigue. The design of aircraft structure accounting for wakes is not state of the art. The standard design includes dynamic loads from PSD gust analysis and buffet or tuned gust analysis, where the intensities of the gust velocities are defined by military or civil

specifications and buffet intensities are defined from wind tunnel test results. Predictions by analysis of wake velocity fields of different aircraft indicate however that the known maximum gust velocities are exceeded and the time history of the velocities experienced by the affected aircraft during penetration is different for example to the 1-cos gust in the discrete analysis. Moreover, flight test results of the dynamic aircraft response during wake penetration produced evidence for its criticality in several flight regimes. This contribution concentrates on military aircraft and demonstrates several examples of predicted critical wake fields and results from calculated dynamic response during different kind of penetration. Also examples from flight dynamic responses are discussed.

Lucca-Negro, O. and O'Doherty, T.

"VORTEX BREAKDOWN: A REVIEW"

Progress in Energy and Combustion Science, Vol. 27, 2001, pp. 431-481.

This paper reviews the studies undertaken on vortex breakdown over the past 45 years. The paper is structured such that the area is considered in three sections -- experimental, numerical and finally theoretical, and provides a 'guide' to the literature and where necessary directs the reader to more in depth reviews in the specific areas.

Luckner, R.

"MODELING AND SIMULATION OF WAKE VORTEX ENCOUNTERS: STATE-OF-THE-ART AND CHALLENGES"

AIAA Paper No. 2012-4633, August 2012, Minneapolis, Minnesota.

Wake vortices are one of the major constraints on separations between aircraft pairs, as wake vortex encounters (WVEs) can be harmful to other aircraft during any phase of flight. The vortex flow field disturbs the encountering aircraft. This affects pilot's workload, comfort and safety of passengers and crewmembers and it has an impact on structural loads. Pilot workload refers to the effort for compensation of perturbations in aircraft's attitude and flight path. The level of tolerable disturbances and acceptable aircraft response depends on the flight phase. Modeling and simulation of WVEs is an important prerequisite for investigations of this phenomenon in fast-time or in piloted real-time flight simulations. This paper describes how the effects of wake-vortex-induced velocities on aircraft flight dynamics can be modeled and how such models are applied. The model requirements for different applications are discussed e.g. for WVE simulations in real-time, piloted simulator tests or for flight simulator training (real-time models), for risk assessments with fast-time Monte Carlo simulations in the rule making process (fast-time models). An overview on the state-of-the-art of WVE modeling is given, i.e. quality, constraints and maturity of models are discussed and directions for future research are given.

Luckner, R.

"VORTEX ENCOUNTER SEVERITY ASSESSMENT (VESA)"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

Airbus has prepared a methodology to assess the severity of a wake vortex encounter, WVE. This methodology is called Vortex Encounter Severity Assessment (VESA). VESA makes it possible to compare aircraft reactions and the effects of vortex encounters behind various aircraft (for example behind all aircraft in the HEAVY class). VESA is proposed as a tool to support air traffic service providers and national aviation safety regulators, which need assurance of the adequacy of the separation standards, if modifications of the current system are proposed. A potential application is to assess if the operational safety of other airplanes is maintained after introduction of the A380. The presentation describes the methodology.

Luckner, R. and Reinke, A.

"PILOT MODELS FOR SIMULATION OF WAKE VORTEX ENCOUNTERS IN CRUISE"

AIAA Paper No. 2010-7683, Toronto, Canada, August 2010.

This paper describes the development of pilot models for simulation of wake vortex encounters in cruise, which could be used for risk assessments for example using the Airbus encounter risk assessment methodology VESA (Vortex Encounter Severity Assessment). Following a brief literature overview, potential encounter scenarios, and worse-case encounter scenarios for cruise are derived for current air traffic separation standards including Reduced Vertical Separation Minima (RVSM). The preparation, conduct, and analysis of a piloted simulation study of cruise flight wake encounters in an Airbus A330 Full Flight Simulator are explained, the simulator results are evaluated and discussed, and pilot models are proposed for Autopilot and Auto Throttle disengagement and for severity classification.

Luckner, R., Hohne, G. and Fuhrmann, M.

"HAZARD CRITERIA FOR WAKE VORTEX ENCOUNTERS DURING APPROACH"

Aerospace Science and Technology, Vol. 8, 2004, pp. 673-687

Airbus has prepared a methodology to assess the severity of a Wake Vortex Encounter, WVE. This methodology is called Vortex Encounter Severity Assessment (VESA). VESA makes it possible to compare the effect of wake vortices generated by various aircraft on an aircraft that encounters such a vortex. Important elements of VESA are the hazard criteria that rate aircraft reactions during WVEs. They are used to compare WVEs in batch simulations. This paper describes how piloted flight simulations for WVE investigations during landing approach were prepared and how the hazard criteria were developed. This work was part of the European S-WAKE program.

Luckner, R., Hohne, G. and Fuhrmann, M.

"HAZARD CRITERIA FOR WAKE VORTEX ENCOUNTERS DURING APPROACH"

DLR Congress 2003, November 2003, Munchen, Germany.

Airbus has prepared a methodology to assess the severity of a Wake Vortex Encounter, WVE. This methodology is called Vortex Encounter Severity Assessment (VESA). VESA makes it possible to compare the effect of wake vortices generated by various aircraft on an aircraft that encounters such a vortex. Important elements of VESA are the hazard criteria that rate aircraft reactions during WVEs. They are used to compare WVEs in batch simulations. This paper describes how piloted flight simulations for WVE investigations during landing approach were prepared and how the hazard criteria were developed. This work was part of the European S-WAKE program.

Ludin, H. B., Omar, A. A. and Asrar, W.

"NUMERICAL STUDY OF THE EFFECT OF SPOILER CONFIGURATION ON WAKE VORTEX ALLEVIATION"

Journal of Aerospace Engineering, Vol. 28, No. 3, 2015, pp. 04014077-1 -- 04014077-26.

A numerical investigation was undertaken to evaluate the capabilities of a differential spoiler setting (DSS) in modifying the spanwise wing load and reducing the hazard of wake vortices imposed on a following aircraft. Numerical simulations were carried out on a scaled, half-model aircraft under a high lift configuration (HCL) condition for two outboard loading cases and two inboard loading cases in addition to the baseline configuration case. The study has covered the near-wake field and the extended near-wake field regions. The results are presented in terms of velocity contours, vorticity contours, tangential velocity, circulation, and streamlines at several measurement sections downstream, namely, at $x/b = 0.345$, $x/b = 0.444$, $x/b = 0.658$, $x/b = 1.794$, and $x/b = 4.484$ measured from the wing-tip trailing edge. Comparison between numerical simulations and experimental results has shown good agreement in terms of lift coefficients for all cases and acceptable agreement in terms of maximum cross-flow velocity, maximum normalized total circulation, and maximum-induced rolling moment. However, in some cases the agreement is not good. Evaluation of the results has shown promising outcomes for the inboard loading cases compared with the outboard loading cases, which agree with the experimental results. The interaction between spoilers' wake and the outboard flap tip vortex of the inboard loading cases reduces the magnitude of the tangential velocity and circulation of the wing tip vortex, delays vortex merging to a farther distance downstream, and thus, minimizes the induced rolling moment imposed on the following aircraft. Therefore, DSS can be considered a promising technique in wake vortex alleviation that can be used commercially in the future. The only limitation of this study is the need for more sophisticated computational resources to benefit from using finer mesh, which can minimize the difference between numerical and experimental results. This should therefore enable extending the study of wake vortices to the very far-wake field or up to a distance where the following aircraft is usually located.

Ludweig, H.

"ERGANZUNG ZU DER ARBEIT: 'STABILITAT DER STROMUNG IN EINEM ZYLINDRISCHEN RINGRAUM'"

Z. Flugwiss., Vol. 11, No. 9, 1961, pp. 359-361.

In a former report the frictionless, helical flow in a cylindrical annulus has been investigated for stability with reference to the occurrence of helical vortices, in analog to the well-known Taylor annular vortices, and a corresponding stability criterion has been given. In this report the author shows that helical disturbance vortices of a more general kind might as well occur in case of such flows, these disturbance vortices somewhat further limiting the formerly indicated region of stability. A stability criterion being modified correspondingly is given.

Ludwig, H.

"VORTEX BREAKDOWN"

DLR-FB-70-40, September 1970, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt, Göttingen, West Germany

Vortex breakdown, an abrupt change in the velocity distribution of a vortex, is often observed under quite different conditions. The various theories for the explanation of the phenomenon are discussed. It is concluded that various physical phenomena may cause a vortex breakdown, so that it is not possible to explain all observed breakdown processes by one theory only.

Ludwig, H.

"AN EXPLANATION OF AN INSTABILITY IN FREE VORTEX CORES OCCURRING ABOVE DELTA WINGS"

Z. Flugwiss., Vol. 10, No. 6, June 1962, pp. 242-249

By rolling up the surfaces of discontinuity originating from the leading edge of delta wings, free vortex cores are formed above the wing. In case of greater angles of incidence, the flow in these vortex cores shows an instability which abruptly produces strong turbulence. An explanation is given of this instability being a 'frictionless instability' of the vortex core flow by increasing helical interference vortices. [In German.]

Ludwig, H.

"INTERPRETATION OF VORTEX BREAKDOWNS WITH THE AID OF THE THEORY OF STABILITY OF FLOWS WITH HELICAL STREAMLINES"

Z. Flugwiss., Vol. 13, No. 12, December 1965, pp. 437-442

The breakdown of the vortices over delta wings is interpreted as instability in the sense of the theory of stability of flows. The manner in which the breakdown progress ought to evolve is investigated in detail according to the theory and the results are compared with recent experimental investigations. [In German.]

Luebs, A. B., Bradfute, J. G. and Ciffone, D. L.

"EFFECTS OF SPOILERS AND GEAR ON B-747 WAKE VORTEX VELOCITIES"

NASA TM X-73197, August 1976, NASA Ames Research Center, Moffett Field, CA

Vortex velocities were measured in the wakes of four configurations of a 0.61-m span model of a B-747 aircraft. The wakes were generated by towing the model underwater in a ship model basin. Tangential and axial velocity profiles were obtained with a scanning laser velocimeter as the wakes aged to 35 span lengths behind the model. A 45 deg deflection of two outboard flight spoilers with the model in the landing configuration resulted in a 36 percent reduction in wake maximum tangential velocity, altered velocity profiles, and erratic vortex trajectories. Deployment of the landing gear with the inboard flaps in the landing position and outboard flaps retracted had little effect on the flap vortices to 35 spans, but caused the wing tip vortices to have: (1) more diffuse velocity profiles; (2) a 27 percent reduction in maximum tangential velocity; and (3) a more rapid merger with the flap vortices.

Luers, J. K.

"A MODEL OF WIND SHEAR AND TURBULENCE IN THE SURFACE BOUNDARY LAYER"

NASA CR-2288, July 1973, University of Dayton, Dayton, OH.

A model of wind and turbulence has been described for the surface boundary layer. The wind structure in the surface layer is a function of the surface parameters, stability, and height. The surface parameters considered are Z zero, the surface roughness length; u star, the surface friction velocity; and d , the zero plane displacement height. The stability parameter, Z/L , where L is the Monin-Obukov stability length, describes the thermal effect on the wind profile. The logarithmic wind profile is used to describe the mean wind field in the neutral boundary layer, and a logarithmic profile with a stability defect is used to describe the stable and unstable atmospheric conditions. For the very stable conditions, the logarithmic wind law does not hold. Under this condition, the layers of the atmosphere become disconnected and large-scale frontal motions are the predominant factor in defining the wind profile. Figures are presented which represent some typical wind profiles in the very stable condition. The Dryden spectral function was chosen to represent the statistical properties of turbulence. The parameters of the Dryden model, σ and L (scale length), are specified as functions of stability, height, and surface conditions for each component of turbulence. The interrelationship between the components of σ and L are constrained to satisfy a condition of local isotropy at large wave numbers.

Luffsey, W. S.

"AIRCRAFT WAKE TURBULENCE"

Safe Engineering, Vol. 3, November 1969, pp. 21-22

Review of the questions posed and tests called for by the problem of aircraft wake turbulence. Available information on wake characteristics is very limited. Tests conducted toward gaining the knowledge required are described. The test methods applied include hot-film anemometry from towers in whose proximity aircraft are flown and wake penetrations by aircraft instrumented with three-axis linear accelerometers, multichannel recording oscillograph, and motion picture cameras providing photo coverage of contrail outlined vortices. It is believed that data from planned testing should ultimately result in a meaningful and practical solution to the problem.

Lugan, S., Bricteux, L., Macq, B., Sobieski, P., Winckelmans, G. and Douchamps, D.

"SIMULATION OF LIDAR-BASED AIRCRAFT WAKE VORTEX DETECTION USING A BI-GAUSSIAN SPECTRAL MODEL"

IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2007), July 2007, Barcelona, Spain

A new spectral model of the return signal from a LIDAR Doppler wake vortex detector is proposed. It has been experimentally discovered during ground-based and flight test campaigns but suffered a lack of theoretical evidence. Using high resolution fluid simulations of wake vortices, we highlight the physical meaning of this model. Comparisons with the traditional single Gaussian model show the superiority of this new approach is consistent with previous experimental results.

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Lugovtsov, B. A.

"ASYMPTOTIC BEHAVIOR OF THE FAR REGION OF TURBULENT WAKE VORTICES"

Journal of Applied Mechanics and Technical Physics, Vol. 40, No. 2, 1999, pp. 198-208.

An approximate mathematical model, formulation of the problem, and its approximate solution are proposed for the far region of a turbulent vortex wake past a moving body, where the departure of the horizontal velocity component from the uniform flow is slight. It is assumed that the single important parameter that defines the main flow characteristics in this region is the vortex momentum per unit length produced in the fluid by the lift equal to the weight of the moving body uncompensated by the buoyancy force. Thus, the flow is self-similar, and the self-similarity law determines the intensity, shape, and location of vortex lines as functions of the downstream distance with accuracy up to a constant factor, which cannot be determined theoretically and should be obtained by comparison of theory with experiment. A boundary-value problem is formulated to determine the flow structure of vortex lines (vorticity distribution). A solution of the problem is obtained numerically in the limit of 'vanishing turbulent viscosity.' The variation in the maximum velocity of a vortex line with distance, determined by self-similarity, is in agreement with available experimental data.

Lugt, H. J.

"VORTEX BREAKDOWN IN ATMOSPHERIC COLUMNAR VORTICES"

American Meteorology Society, Vol. 70, December 1989, pp. 1526-1537

Vortex breakdown occurs in tornadoes and waterspouts. This phenomenon may give information on the state and future behavior of those whirlwinds. Because of the rarity of recorded events, archival sources are consulted for qualitative descriptions from earlier times and compared with contemporary sources. Drawings and eyewitness reports from earlier times, rare photographs, movies, and observations from recent years indicate the occurrence of vortex breakdown in tornadoes and waterspouts near the ground, in the midsection of the funnel, and close to or inside the parent cloud. Since the contour of the whirlwind's funnel is delineated only by markers in the form of condensates, dust, or other debris, these markers may distort or obscure the evidence of vortex breakdown. This is a likely reason for the rare observation and identification of vortex breakdown which might be more common in whirlwinds than has been previously thought. According to the records examined, meteorologists deserve the honor for discovering and describing vortex breakdown long before the systematic investigation of recent years.

Lum, C. W., Sandhu, N., Diebold, J. M., Woodard, B. S. and Bragg, M. B.

"THE APPLICATION OF A FIVE-HOLE PROBE WAKE-SURVEY TECHNIQUE TO THE STUDY OF SWEEPED WING ICING AERODYNAMICS"

AIAA Paper 2017-4374, June 2017, Denver, CO.

This paper describes a wake survey system used to improve the understanding of the underlying flowfield and aerodynamics of a swept wing with ice accretions. This system allows the rapid collection and analysis of large amounts of flowfield data by utilizing an array of five-hole probes on a precisely controlled traverse arm. Flowfield structure on the surface of the wing is acquired using an oil flow visualization technique and correlated to the associated wake survey. This method allows quantitative

calculations such as spanwise lift and drag to be compared with qualitative measurements and observations to enhance the understanding of the aerodynamics of wings containing ice accretions. Wind tunnel tests for a range of configurations are presented and analyzed in this paper. Results based on this wake survey method are compared with traditional measurement techniques such as force balance measurements to assess their accuracy.

Lund, F.

"SOUND-VORTEX INTERACTION IN INFINITE MEDIA"

Lecture Notes in Physics, Vol. 586, 2002, pp. 112-159

This lecture describes the interaction of sound and vorticity in infinite media. The scattering of sound by the vorticity is described. Recent results on ultrasound propagation through a disordered flow are given.

Lund, F. and Zabusky, N. J.

"A NEW APPROACH TO THE EFFECT OF SOUND ON VORTEX DYNAMICS"

Phys. Fluids, Vol. 30, No. 8, August 1987, pp. 2306-2307

Two questions are asked, and answered, concerning the dynamics of vortex filaments in a three-dimensional slightly compressible fluid with constant sound speed: What is the flow (including the sound) generated by a vortex in prescribed motion? What is the response of a test vortex to an external flow? The first question is answered by the convolution of a Green's function with a source localized at the filament; the second by a differential equation valid in the localized induction approximation. A variational principle encompassing both problems is also provided.

Lundquist, J. K. and Bariteau, L.

"DISSIPATION OF TURBULENCE IN THE WAKE OF A WIND TURBINE"

Boundary-Layer Meteorology, Vol. 154, 2015, pp. 229-241.

The wake of a wind turbine is characterized by increased turbulence and decreased wind speed. Turbines are generally deployed in large groups in wind farms, and so the behavior of an individual wake as it merges with other wakes and propagates downwind is critical in assessing wind-farm power production. This evolution depends on the rate of turbulence dissipation in the wind-turbine wake, which has not been previously quantified in field-scale measurements. In situ measurements of winds and turbulence dissipation from the wake region of a multi-MW turbine were collected using a tethered lifting system (TLS) carrying a payload of high-rate turbulence probes. Ambient flow measurements were provided from sonic anemometers on a meteorological tower located near the turbine. Good agreement between the tower measurements and the TLS measurements was established for a case without a wind-turbine wake. When an operating wind turbine is located

between the tower and the TLS so that the wake propagates to the TLS, the TLS measures dissipation rates one to two orders of magnitude higher in the wake than outside of the wake. These data, collected between two and three rotor diameters D downwind of the turbine, document the significant enhancement of turbulent kinetic energy dissipation rate within the wind-turbine wake. These wake measurements suggest that it may be useful to pursue modelling approaches that account for enhanced dissipation. Comparisons of wake and non-wake dissipation rates to mean wind speed, wind-speed variance, and turbulence intensity are presented to facilitate the inclusion of these measurements in wake modelling schemes.

Lundry, J. L.

"INITIAL DEVELOPMENT OF A WAKE TURBULENCE ASSESSMENT SYSTEM"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 183-193

The initial development of a computer software system for wake vortex technology is discussed. The system is intended for use in the preliminary design of new airplanes. Several overall objectives are listed, including the prediction of hazard as a function of geometry and flight conditions of the wake-producing and wake-penetrating airplanes, low cost of use, adaptability to new technology, and an explanation of currently known alleviation concepts. Essential elements of a Wake Turbulence Assessment System are listed, and an upper-level system design is presented. Candidate technology for system elements is discussed. Prototype code has been produced for the initial wake rollup and for the wake penetration. Initial results of these two modules are compared with experimental data, and are promising. The comparisons also show the importance of considering the low Reynolds number at which model studies of wake penetration are conducted.

Lunnon, B.

"TURBULENCE EVENTS INTERPRETED BY VORTEX ROLLS"

In *Aviation Turbulence*, edited by R. Sharman and T. Lane, Chapter 4, 2016, Springer International Publishing Switzerland, pp. 83-94.

The severity of an aircraft encounter with turbulence is usually quantified by reference to the aircraft normal acceleration. For an encounter between an idealized aircraft and an idealized vortex, the acceleration vector is equal to the cross product of half the vorticity vector with air velocity vector. More realistic expressions for the aircraft acceleration have been derived in the context of aircraft encounters with wake vortices, and, although the scale of wake vortices is smaller than that of naturally occurring vortices, the broad methodology is broadly applicable. This chapter looks both at these idealized cases and more practical issues. Many of the issues touched on are dealt with more comprehensively elsewhere. Two issues are addressed which are particular to the interpretation of turbulence using vortex constructs. Firstly, the feasibility of forecasting vortex characteristics is

addressed. Secondly, a method of representing the significant statistical properties of anisotropic turbulence is suggested.

Lunsford, C. R.

"A CONCEPT FOR PAIRING DEPARTURES FROM PARALLEL RUNWAYS FOR WAKE AVOIDANCE"

ICNS Conf., Bethesda, MD, May 2008

The Paired Departure concept increases the ability to use closely spaced parallel runways for departures by providing an alternate means of avoiding the wake turbulence created by departing Heavy and Boeing 757 aircraft. Wake research over the past thirty years has developed a better understanding of wake movement and decay near the ground. By considering the spacing between the parallel runways at an airport and by establishing a maximum allowable crosswind, a wake-free departure time window can be defined such that it is not possible for a wake to transport to the other runway within that time interval. For airports that can implement the Paired Departure concept, the time that wake-free departures can be enabled could potentially be doubled due to the additional crosswind conditions that can safely be accommodated using the Paired Departure time window. This paper describes the Paired Departure concept, discusses key implementation options and issues, and provides results of an initial analysis of feasibility and potential benefit.

Lunsford, C. R., Smith, III, A. P., Cooper, Jr., W. W., Mundra, A. D., Gross, A. E., Audenaerd, L. F. and Killian, B. E.

"EXPLORATION OF TERMINAL PROCEDURES ENABLED BY NASA WAKEVAS TECHNOLOGIES"

NASA-CR-2004-213023, January 2004, Mitre Corporation, McLean, VA

The National Aeronautics and Space Administration (NASA) tasked The Mitre Corporation's Center for Advanced Aviation System Development (CAASD) to investigate potential air traffic control (ATC) procedures that could benefit from technology used or developed in NASA's Wake Vortex Advisory System (WakeVAS). The task also required developing an estimate of the potential benefits of the candidate procedures. The main thrust of the investigation was to evaluate opportunities for improved capacity and efficiency in airport arrival and departure operations. Other procedures that would provide safety enhancements were also considered. The purpose of this investigation was to provide input to the WakeVAS program office regarding the most promising areas of development for the program. A two-fold perspective was desired: First, identification of benefits from possible procedures enabled by both incremental components and the mature state of WakeVAS technology; second identification of procedures that could be expected to evolve from the current Federal Aviation Administration (FAA) procedures. The evolution of procedures should provide meaningful increments of benefit and a low risk implementation of the WakeVAS technologies.

Lunsford, C., Audenaerd, L., Cooper, W., Mundra, A., Tittsworth, J. and Cormier, T.

"THREE PHASES OF WAKE PROCEDURES: AN INTEGRATED CAPACITY BENEFIT STORY, 2nd Workshop WakeNet2-Europe"

The U.S. Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) are cooperatively working toward developing and implementing ATC procedures and wake turbulence technology that will safely increase arrival and departure capacity at key airports. These improvements will be achieved in three major phases with each phase including additional weather prediction and wake avoidance aspects. MITRE/CAASD has been conducting assessments of capacity benefits of these proposals. In particular, it has been analyzing incremental benefits for the major evolutionary phases, as well as potential smaller steps within each phase. These analyses are intended to help determine trade-offs between potential benefits and overall technology requirements. The analyses also examine sensitivities to operationally meaningful parameters such as accuracies of weather forecast parameters. This presentation provides results regarding the relative capacity increases of incremental steps spanning the three phases of deployment. Both arrival and departure procedures are addressed. Benefits will be compared in terms of increases in peak hour arrival and departure capacity and their sensitivities to certain key prediction parameters.

Lunsford, C., Mundra, A., Audenaerd, L., Cheng, J., Devlin, C., Gross, A., Mayer, R., Sherry, J., Bryant, W., Johnson, E. and McKissick, B.

"WIND DEPENDENT CONCEPTS FOR WAKE AVOIDANCE: A COMPARATIVE ANALYSIS OF CAPACITY BENEFITS AND IMPLEMENTATION RISKS"

24th Digital Avionics Systems Conference, Vol. 1, 2005, pp. 3.A.4-1--3.A.4-16

The FAA and NASA are jointly embarking on a multi-phased research and development program to develop and implement wake vortex avoidance solutions that can safely reduce separations and improve capacity at airports in the NAS. Many options have been proposed by the wake turbulence community and it is necessary to focus research efforts on the most promising solutions. As part of its WakeVAS initiative, NASA has investigated the research difficulty and cost for candidate operational enhancements through a Conops Evaluation Team (CET). This team included participation by stakeholders from many research, system engineering, system development, pilot, and controller organizations. The operational enhancements that were evaluated included wind-dependent concepts for arrivals to Closely Spaced Parallel Runways (CSPRs), departures from CSPRs operated as a single runway, arrivals to single runways, and departures from single runways. To complement this work and help provide the information necessary for NASA to focus their research program toward the most promising concepts, MITRE/CAASD performed an analysis of the potential capacity benefit, opportunity for application, and implementation risk for each arrival and departure concept evaluated by the CET. This paper provides an overview of the direction in which NASA research will proceed and the analysis results that help support this decision.

Luo, J., Zhu, L. and Yan, G.

"NOVEL QUADROTOR FORWARD-FLIGHT MODEL BASED ON WAKE INTERFERENCE"

AIAA Journal, Vol. 53, No. 12, December 2015, pp. 3522-3533.

The traditional aerodynamic model of the quadrotor is almost entirely based on the modeling of a single rotor, ignoring the wake interference among the four rotors in close proximity. Because of the oversimplification of the aerodynamic model, the attitude control and trajectory tracking of the quadrotor is unsatisfactory in high-speed flight. To accurately and effectively control the attitude and trajectory of the quadrotor, this study proposes a quadrotor forward-flight mathematical model considering rotor wake mutual interference, which can be used in flight control. To validate the model, a series of computational-fluid-dynamics analyses were conducted. An integral quadrotor model and an isolated rotor were analyzed under the same conditions. The mathematical model and results of the computational-fluid-dynamics analyses results provided trends and demonstrated the suitability of the proposed model for high-speed forward flight.

Lush, P. A.

"THE PRESSURE AND VELOCITY FIELDS OF CONVECTED VORTICES"

Journal of Sound and Vibration, Vol. 27, No. 2, February 1973, pp. 266-270

The pressure and velocity fields of convected vortices are calculated for irrotational, incompressible, and inviscid flow and assuming the vortex strength and convection velocity are constant. The case of a single vortex filament and the case of two contrarotating line vortices of equal strength are considered.

Luton, A., Ragab, S. and Telionis, D.

"INTERACTION OF SPANWISE VORTICES WITH A BOUNDARY LAYER"

Physics of Fluids, Vol. 7, No. 11, November 1995, pp. 2757-2765.

The interaction of a spanwise vortex with a boundary layer has been numerically simulated using a fractional-step method. The incompressible Navier-Stokes equations are solved to accurately predict the strong viscous-inviscid interaction between a vortex either near or embedded within a boundary layer of comparable size. A strong vortex induces an eruption and the production of a secondary vortex. The secondary vortex causes the primary vortex to rebound, a response observed in many previous experiments and numerical simulations. However, weaker vortices as well do not follow the inviscid trajectory despite the absence of a secondary vortex. Rather than creating vorticity at the wall, a weaker vortex mainly redistributes the vorticity of the boundary layer, pulling it away from the wall. The redistributed vorticity alters the path of the vortex. In the laminar cases studied the decay of the vortex is not significantly altered by the boundary layer.

Luton, A., Ragab, S. and Telionis, D.

"INTERACTION OF SPANWISE VORTICES WITH A BOUNDARY LAYER"

AIAA Paper No. 1994-2377, Colorado Springs, CO, June 1994

The interaction of a spanwise vortex with a boundary layer has been numerically simulated using a fractional-step method. The incompressible Navier-Stokes equations are solved to accurately predict the strong viscous-inviscid interaction between a vortex either near or embedded within a boundary layer of comparable size. A strong vortex induces an eruption and the production of a secondary vortex. The secondary vortex causes the primary vortex to rebound, a response observed in many previous experiments and numerical simulations. However, weaker vortices as well do not follow the inviscid trajectory despite the absence of a secondary vortex. Rather than creating vorticity at the wall, a weaker vortex mainly redistributes the vorticity of the boundary layer, pulling it away from the wall. The redistributed vorticity alters the path of the vortex. In the laminar cases studied the decay of the vortex is not significantly altered by the boundary layer.

Luton, J. A. and Ragab, S. A.

"THE THREE-DIMENSIONAL INTERACTION OF A VORTEX PAIR WITH A WALL"

Physics of Fluids, Vol. 9, No. 10, October 1997, pp. 2967-2980.

The interaction of vortices passing near a solid surface has been examined using direct numerical simulation. The configuration studied is a counter-rotating vortex pair approaching a wall in an otherwise quiescent fluid. The focus of these simulations is on the three-dimensional effects, of which little is known. To the authors' knowledge, this is the first three-dimensional simulation that lends support to the short-wavelength instability of the secondary vortex. It has been shown how this Crow-type instability leads to three dimensionality after the rebound of a vortex pair. The growth of the instability of the secondary vortex in the presence of the stronger primary vortex leads to the turning and intense stretching of the secondary vortex. As the instability grows the secondary vortex is bent, stretched, and wrapped around the stronger primary. During this process reconnection was observed between the two secondary vortices. Reconnection also begins between the primary and secondary vortices but the weaker secondary vortex dissipates before the primary, leaving reconnection incomplete. Evidence is presented for a new type of energy cascade based on the short-wavelength instability and the formation of continual smaller vortices at the wall. Ultimately the secondary vortex is destroyed by stretching and dissipation leaving the primary vortex with a permanently distorted shape but relatively unaffected strength compared to an isolated vortex.

Ma, B.-F. and Jiang, H.-G.

"ESTIMATION OF PERSPECTIVE ERRORS IN 2D2C-PIV MEASUREMENTS FOR 3D CONCENTRATED VORTICES"

Experiments in Fluids, Vol. 59, 2018, pp. 101-1 to 101-14.

Two-dimensional planar PIV (2D2C) is still extensively employed in flow measurement owing to its availability and reliability, although more advanced PIVs have been developed. It has long been recognized that there exist perspective errors in velocity fields when employing the 2D2C PIV to

measure three-dimensional (3D) flows, the magnitude of which depends on out-of-plane velocity and geometric layouts of the PIV. For a variety of vortex flows, however, the results are commonly represented by vorticity fields, instead of velocity fields. The present study indicates that the perspective error in vorticity fields relies on gradients of the out-of-plane velocity along a measurement plane, instead of the out-of-plane velocity itself. More importantly, an estimation approach to the perspective error in 3D vortex measurements was proposed based on a theoretical vortex model and an analysis on physical characteristics of the vortices, in which the gradient of out-of-plane velocity is uniquely determined by the ratio of the maximum out-of-plane velocity to maximum swirling velocity of the vortex; meanwhile, the ratio has upper limits for naturally formed vortices. Therefore, if the ratio is imposed with the upper limits, the perspective error will only rely on the geometric layouts of PIV that are known in practical measurements. Using this approach, the upper limits of perspective errors of a concentrated vortex can be estimated for vorticity and other characteristic quantities of the vortex. In addition, the study indicates that the perspective errors in vortex location, vortex strength, and vortex radius can be all zero for axisymmetric vortices if they are calculated by proper methods. The dynamic mode decomposition on an oscillatory vortex indicates that the perspective errors of each DMD mode are also only dependent on the gradient of out-of-plane velocity if the modes are represented by vorticity.

Ma, K.-L. and Zheng, Z. C.

"VOLUME VISUALIZATION OF AIRPLANE WAKE VORTICES"

In: Flow Visualization VII: Proceedings of the 7th International Symposium on Flow Visualization, Seattle, WA, September 1995, pp. 586-591

In this paper, we describe the use of volume rendering for visualizing unsteady 2D aircraft wake vortex computations. The problem we consider here includes crosswind effects. It involves a pair of wake vortices interacting with each other and, at the same time, with the ground. Ray-traced volume rendering is used to visualize the desirable vortex tube by first making a matte volume during the core tracing process. Volume rendering offers realistic visualization of the physical phenomena and allows us to see not only the core boundaries but also the core content.

Ma, K.-L. and Zheng, Z. C.

"3D VISUALIZATION OF UNSTEADY 2D AIRPLANE WAKE VORTICES"

NASA Contractor Report 194931 (and ICASE Report 94-45), June 1994, Institute for Computer Applications in Science and Engineering, Hampton, VA.

Air flowing around the wing tips of an airplane forms horizontal tornado-like vortices that can be dangerous to following aircraft. The dynamics of such vortices, including ground and atmospheric effects, can be predicted by numerical simulation, allowing the safety and capacity of airports to be improved. In this paper, we introduce three-dimensional techniques for visualizing time-dependent, two-dimensional wake vortex computations, and the hazard strength of such vortices near the ground.

We describe a vortex core tracing algorithm and a local tiling method to visualize the vortex evolution. The tiling method converts time-dependent, two-dimensional vortex cores into three-dimensional vortex tubes. Finally, a novel approach calculates the induced rolling moment on the following airplane at each grid point within a region near the vortex tubes and thus allows three-dimensional visualization of the hazard strength of the vortices. We also suggest ways of combining multiple visualization methods to present more information simultaneously.

Ma, K.-L. and Zheng, Z. C.

"3D VISUALIZATION OF UNSTEADY 2D AIRPLANE WAKE VORTICES"

Proceedings of the IEEE Conf. on Visualization, October 1994, Washington, DC

Air flowing around the wing tips of an airplane forms horizontal tornado-like vortices that can be dangerous to following aircraft. The dynamics of such vortices, including ground and atmospheric effects, can be predicted by numerical simulation, allowing the safety and capacity of airports to be improved. In this paper, we introduce three-dimensional techniques for visualizing time-dependent, two-dimensional wake vortex computations, and the hazard strength of such vortices near the ground. We describe a vortex core tracing algorithm and a local tiling method to visualize the vortex evolution. The tiling method converts time-dependent, two-dimensional vortex cores into three-dimensional vortex tubes. Finally, a novel approach calculates the induced rolling moment on the following airplane at each grid point within a region near the vortex tubes and thus allows three-dimensional visualization of the hazard strength of the vortices. We also suggest ways of combining multiple visualization methods to present more information simultaneously.

Ma, Y., Hu, M., Yin, J. and Tian, W.

"COLLABORATIVE SEQUENCING AND SCHEDULING METHOD FOR ARRIVAL AND DEPARTURE TRAFFIC FLOW IN MULTI-AIRPORT TERMINAL AREA"

Acta Aeronautica et Astronautica Sinica, Vol. 38, No. 2, February 2017, pp. 320222-1 to 320222-13.

To cope with the increasing serious situation of flight conflict, airspace congestion and flight delay in the metropolis and metropolitan areas, the problem of arrival and departure traffic flow collaborative scheduling in multi-airport terminal area is studied. Considering the wake turbulence separation, runway operating separation, time window, airport capacity, and other constraints, the integrated traffic flow scheduling model for arrival and departure is built, in which the concept of flight satisfaction degree is introduced in the multi-dimensional-temporal perspective. Then an elitist non-dominated sorting generic algorithm (NSGA-II) is designed to search for Pareto optimal solutions of the proposed scheduling model in multi-airport terminal area. Simulation results show that the arrival and departure traffic flow scheduling in multi-airport terminal area is optimized using the proposed model which can also reduce the flight delay time, significantly increase the total satisfaction degree of flight, and ensure that the airspace resources in multi-airport terminal area are fairly and evenly used. Compared to the classic strategy of First-Come-First-Served, the integrated scheduling model has more significant effect

on the optimization of flights, and the proposed method can reduce the flight delay time to a certain extent. [In Chinese.]

Maalouf, B., Dobrev, I. and Massouh, F.

"VORTEX STRUCTURE IN THE WAKE OF A WIND TURBINE ROTOR"

19th French Congress of Mechanics, August 2009, Marseille, France.

This paper describes the wind tunnel investigation of vortex wake flow downstream of a three-blade rotor of a horizontal-axis wind turbine. The phase-locked measurements are carried out by means of particle image velocimetry in several azimuth planes. To widen the explored area, the investigated velocity field is divided into several windows with some overlapping. An algorithm based on circulation calculation permits to find the vortex core centers and to extract velocity, vorticity and circulation with respect to these vortex centers. After the conditionally averaging, the net vortex induced velocity is extracted and the characteristics of the tip vortices trailing from consecutive blades are evaluated. The obtained results for the tangential velocity are analyzed and coefficients of Vatistas vortex model are evaluated. These coefficients are found to be different from the case of helicopter tip vortices. Finally, velocity field analysis shows how trailing vortex circulation, vortex core diameter and peak tangential velocity vary as a function of the vortex age.

Maas, S. J. and Scoggins, J. R.

"STRUCTURE OF ATMOSPHERIC TURBULENCE IN THE FRICTION LAYER BELOW 500 METERS"

NASA CR-2650, February 1976, Texas A&M University, College Station, TX.

Data consisting of measurements of wind direction and speed, vertical velocity, and temperature from several levels on the 444-m tower near Oklahoma City instrumented by the National Severe Storms Laboratory were analyzed to determine the nature of turbulence in the lowest 500 m of the friction layer. Turbulence quantities were calculated from the covariances between observed variables over periods ranging from 5 min to 1 hr. It was found that in some cases parameters such as mean wind speed, shearing stress, and vertical heat flux could be expressed by simple equations for periods of 15 min to 1 hr. Changes in these quantities with time are related to changes in vertical motion and stability. Power spectra were calculated for sequential 15-min, 30-min, and 1-hr periods for several levels on the tower. The effects of stability, wind speed, and surface roughness on the spectra of longitudinal and lateral velocity are examined, along with the effect of height on the spectrum of vertical velocity. The existence of an inertial subrange in the spectra of the horizontal velocity components also is evidenced. The region penetrated by the tower is shown to be composed of a lower region in which mechanical turbulence dominates and an upper region dominated by convective turbulence.

MacCready Jr., P. B.

"STANDARDIZATION OF GUSTINESS VALUES FROM AIRCRAFT"

Journal of Applied Meteorology, Vol. 3, August 1964, pp. 439-449.

A universal turbulence standardization technique is described which is based quantitatively on the atmospheric turbulence itself rather than on the effects it produces on an aircraft. It provides a single turbulence intensity number which may be measured continuously in flight in a variety of ways, and, with knowledge of the aircraft type and speed, can be linearly related to the rms value of vertical accelerations of the aircraft. The universal intensity number concept as applied here is an extension for aircraft use of the inertial subrange concept of atmospheric turbulence. In the inertial subrange all the statistical properties of turbulence of wavelengths less than a few hundred meters (the wavelength range which dominates gust loading for most aircraft) can be simply related to a single number. The intensity measurement also has value as a basic meteorological parameter, and has proven to be particularly useful in diffusion studies. The intensity scale is derived from various turbulence power spectrum studies. A larger background of data on turbulent distributions is also available because existing statistical discrete gust and continuous gust data can be fitted approximately to this standardization procedure, and meteorological studies have also given estimates of the distribution of this intensity number. The intensity number can be found from virtually any device moving through the air, as well as by some indirect meteorological means. A particular version of a universal turbulence indicator is described. The universal turbulence intensity rating provides a standard for communication about turbulence and for the collection of statistical turbulence information. It also provides a quantitative method of relating aircraft response and pilot 'feel' to the turbulence, so that the pilot can select or preselect the appropriate speed for specific missions.

MacCready, Jr., P. B.

"AN ASSESSMENT OF DOMINANT MECHANISMS IN VORTEX-WAKE DECAY"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 289-304

Predicting the transport and decay of the organized vortex system for various aircraft types, flight modes, and meteorological conditions requires clear identification of the various significant factors and mechanisms involved in the transport/decay process. Outside of the ground effect, the dominant factors include the circulation and core characteristics of the vortices, the turbulence in the wake and in the environment, and the thermal stability of the environment. The environmental factors are sometimes dominant; the vortex wakes from an airplane operating in two different meteorological regimes can differ by an order of magnitude in decay and by an order of magnitude in decent distance.

MacCready, Jr., P. B. and Bate, Jr., E. R.

"AIRCRAFT VORTEX-WAKE EFFECTS ON PARTICLE TRANSPORT, BREAKUP, AND COALESCENCE"

AV FR-301, January 1973, AeroVironment Inc., Pasadena, C.

The vortex sheet from an aircraft wing and the associated organized vortex pair in the aircraft's wake constitute a flow field with strong shears and accelerations which may have important consequences on the local microphysics of natural clouds and on certain cloud seeding techniques. Calculations are made of the trajectories of small (5-micron radius) droplets and large (50-micron radius) droplets released in the cores of two representative vortex situations (corresponding to a C-130 and a Piper Aztec). The small droplets only move out to a radius of 1m or so before their outflow speed is down to negligible value (assumed to be 20 cm/sec, comparable to the cloud turbulence). The large droplets are spun out about 5m for the C-130 and 1-1/2m for the Apache. The speed of the droplets relative to the air is everywhere too slow to cause droplet breakup.

MacCready, Jr., P. B. and Lissaman, P. B. S.

"ASSESSMENT OF ATMOSPHERIC EFFECTS ON THE BEHAVIOR OF AIRCRAFT WAKE VORTICES"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 310-315

The transport and decay of an aircraft-generated vortex system depends on the characteristics of the generating aircraft, the proximity to the ground, and on atmospheric factors - the turbulence field, thermal stability, and mean wind shears throughout the region traversed by the vortex system. The number of variables involved, the statistical nature of the phenomena, and the difficulty of performing definitive field tests make the development of a comprehensive theory of vortex transport and decay an elusive goal, but significant strides have been made. This paper seeks to illuminate some of the main points, with more emphasis on dominant factors than on completeness or rigorosity.

MacCready, Jr., P. B. and Tombach, I. H.

"INFLIGHT VALIDATION OF VORTEX BEHAVIOR AND HAZARD MODELS IN THE VORTEX WAKES OF JET TRANSPORT AIRCRAFT"

AV-FR-502, January 1975, AeroVironment, Pasadena, CA

A plan is presented for an experimental program to validate three models - flow field, vehicle response, hazard region - which give (respectively) the vortex flow field as a function of generating aircraft characteristics and atmospheric characteristics; the response of an aircraft, with certain stability and control characteristics, to an encounter with the vortex system; and the limits of the hazard volume to be avoided by a specific aircraft.

Machado, C. R.

"AN ANALYSIS OF METEOROLOGICAL MEASUREMENTS USING A MINIATURE QUAD-ROTOR UNMANNED AERIAL SYSTEM"

MS Thesis, June 2015, Naval Postgraduate School, Monterey, CA.

Naval operational weather products, especially EM prediction, often fail to capture key meteorological features in the boundary layer due to the absence of high-resolution profile data. Quad-rotor small unmanned aerial systems (sUAS) with meteorological sensing capabilities may provide a solution for acquiring vertical profile data at sea. With the use of an RS92 radiosonde, InstantEye sUAS, and a calibrated sensing tower, we analyzed the effects a quad-rotor had on the accuracy of temperature and pressure profiles in the surface layer. In unstable atmospheres, temperature measurements made in the surface layer are as accurate as the manufacturer's claimed accuracy. In stable atmospheres, mixing occurs below 1.3 m, while above 2 m, sampled air comes from as much as 2 m aloft. The InstantEye's rotors contribute to the variation in temperature measurement, and this effect is strongest near the surface. The variations introduced by the prop-wash helped suppress natural variations from turbulent fluctuations, but are still present above the surface layer. The InstantEye also introduces a 0.12 hPa pressure bias while in flight due to rotor-induced lift.

Machol, R. E.

"WAKE VORTICES - A PRIMER"

FAA Aviation Safety J., Vol. 3, No. 1, 1993, pp. 16-19

The FAA must balance safe separation with the need to operate an efficient air traffic control system. The FAA believes research and operational experience show current standards are safe, but with the capacity issue, wake vortex issues are in the forefront when it comes to considering closer separation standards.

Mack, G. R.

"WAKE VORTICES' EFFECT AND THE NEED FOR PROMPT ACTION - A U.S. VIEW"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 2-1 to 2-5

As we approach the next century, wake vortices have become one of the key limiting factors in airport capacity. Despite the significant effort expended on wake vortices over the years, several issues remain unresolved. The major issues that must be resolved before separation criteria can be refined are as follows: (1) defining the basis for wake turbulence separation; (2) determining the far-field characteristics of the wake; (3) understanding the influence of meteorological conditions on these characteristics; (4) evaluating the significance of the wake characteristics to safety of flight; and (5) developing the technology required to mitigate capacity constraints associated with wake turbulence. Regulatory agencies, airlines, manufacturers, the piloting and ATC communities, and research institutions must team together to ensure that the affected segments of the industry are engaged together, using their collective skills to achieve both the highest possible safety level and the most efficient operational procedures to meet travel demand.

Mack, L. M.

"THE COMPRESSIBLE VISCOUS HEAT-CONDUCTING VORTEX"

Journal of Fluid Mechanics, Vol. 8, 1960, pp. 284-292.

The plane, steady, laminar vortex flow of a viscous, heat-conducting perfect gas is treated. Simple relations are obtained for the flow quantities in the irrotational vortex, for arbitrary Prandtl numbers. When the Prandtl number is $1/2$, the irrotational vortex is also isentropic. When the temperature dependence of the viscosity coefficient is considered, the vortex flow is rotational. An exact solution for the rotational vortex is obtained which is suitable for numerical evaluation by successive approximations. Distributions of velocity, temperature, pressure, density, and stagnation temperature through the rotational vortex are given for a typical case.

Mackenzie, A. I.

"MEASURED CHANGES IN C-BAND RADAR REFLECTIVITY OF CLEAR AIR CAUSED BY AIRCRAFT WAKE VORTICES"

NASA TP-3671, November 1997, Langley Research Center, Hampton, VA

Wake vortices from a C-130 airplane were observed at the NASA Wallops Flight Facility with a ground-based, monostatic C-band radar and an antenna-mounted boresight video camera. The airplane wake was viewed from a distance of approximately 1 km, and radar scanning was adjusted to cross a pair of marker smoke trails generated by the C-130. For each airplane pass, changes in radar reflectivity were calculated by subtracting the signal magnitudes during an initial clutter scan from the signal magnitudes during vortex-plus-clutter scans. The results showed both increases and decreases in reflectivity on and near the smoke trails in a characteristic sinusoidal pattern of heightened reflectivity in the center and lessened reflectivity at the sides. Reflectivity changes in either direction varied from -131 to -102 dBm-1; the vortex-plus-clutter to noise ratio varied from 20 to 41 dB. The radar recordings lasted 2.5 min each; evidence of wake vortices was found for up to 2 min after the passage of the airplane. Ground and aircraft clutter were eliminated as possible sources of the disturbance by noting the occurrence of vortex signatures at different positions relative to the ground and the airplane. This work supports the feasibility of vortex detection by radar, and it is recommended that future radar detection be done with Doppler systems.

Mackey, S. M. and Burnham, D. C.

"USE OF A COMMERCIAL WIND SODAR FOR MEASURING WAKE VORTICES"

AIAA Paper No. 2006-2537, Cambridge, MA, May 2006

This paper describes the application of a commercial wind SODAR (SOmatic Detection and Ranging) to the measurement of aircraft wake vortices. Changes in data collection and processing were required to extract vortex location and circulation from the acoustic returns. Sample data are presented, and it is

demonstrated that SODARs represent valuable addition to the existing array of sensors for tracking and characterizing aircraft vortices in-ground effect.

Mackey, S. M., Robins, R., Zhang, Y. and Wang, F. Y.

"EXAMINATION OF THE APPLICABILITY OF NOAA MADIS AIRCRAFT BASED OBSERVATION DATASET FOR WAKE TURBULENCE RESEARCH"

AIAA Paper 2018-2866, June 2018, Atlanta, GA.

This paper summarizes an analysis conducted by the Volpe Center regarding aircraft-based observation (ABO) data from the National Oceanic and Atmospheric Administration (NOAA) MADIS (Meteorological Assimilation Data Ingest System). A series of validation or inter-comparison campaigns that include Eddy Dissipation Rate (EDR), Brunt-Vaisala Frequency (BVF), and Wind are made between NOAA MADIS datasets and ground based remote sensing measurements to establish confidence in and understanding of the ABO data for wake turbulence research application. The NOAA MADIS ABO data are then used to estimate the statistical distributions of the meteorological quantities that impact wake decay in the enroute environment, restricted to a subset of the current commercial flights over the continental United States (CONUS), and to preliminarily explore the likelihood of near best- and worst-case wake turbulence meteorological conditions. The possible implications for enroute wake decay are explored, and use of ABO crosswind data for wake mitigation is discussed.

Mackey, S. M., Wang, F. Y., Wassaf, H. and Soares, M.

"COMPARISON BETWEEN ARRIVAL AND DEPARTURE WAKE VORTEX STATISTICS NEAR THE GROUND"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-002, September 2007, pp. 1049-1054

In-Ground-Effect vortex measurements from arrival and departure aircraft have been made between 2003 and 2007 in a series of pulsed Lidar measurements in St. Louis, USA. These data collections support various objectives outlined in the joint FAA-NASA Wake Turbulence Research Management Plan. Wake turbulence data collection traditionally has been focused on arrival aircraft, leaving their departure counterpart less well understood. In response to the renewed interest internationally in studying vortices from departure aircraft, the present paper summarizes the initial results of comparing the vortex statistics near the ground between arrival and departure vortices generated from similar flight altitude to wingspan ratio and crosswind range. The present study also has the advantage that departure and arrival vortex data are collected from the same site, using the same sensor and the same processing technique, such that the relative characteristics can be revealed with simple statistical techniques and minimizing the potential biases from sensor, airport and processing related considerations. The study to date suggests that departure vortices have similar initial circulations compared to their arrival counterparts, and that the survival probabilities are likewise very similar. There also exists indication that the measured age for wake demise is correlated with environmental turbulence. The overall implication is that statistics compiled and models developed from historical

databases based on arrival vortices can be used at least as a first order estimate for examining departure wake mitigation concepts.

Macrorie, M. and Pauley, W. R.

"EXPERIMENTAL DEVELOPMENT OF SPANWISE VORTEX MODELS WITH STREAMWISE DECAY DUE TO WALL INTERACTION"

AIAA Paper No. 1992-2688, Arlington, VA, April 1992

Results of an experimental investigation of the interaction between convecting two-dimensional spanwise vortex structures and a flat plate are presented. The objective is to provide modeling of convected two-dimensional vortices developing in close interaction with a surface. Vortices of positive and negative circulation are studied at four generator heights above the test surface. The findings support that the strength of the vortices is not strongly affected by the interaction with the surface until the vortex core becomes fully embedded in the boundary layer. When a negative circulation vortex interacts closely with the surface it is quickly destroyed. The streamwise decay of vortices of both senses are studied for a single generator height at five streamwise stations. The results show that the core vorticity of dynamic stall vortices experience an initial decay rate of t^{-1} which is like that predicted for an Oseen vortex. The decay rate is not constant and increases with time. A simple analysis of end-wall effects is used to demonstrate that 3-dimensional effects should be small in this experiment and are not contributing substantially to the vortex decay.

Macrorie, M. and Pauley, W. R.

"EXPERIMENTAL INVESTIGATION OF CONVECTING VORTEX/BOUNDARY-LAYER INTERACTIONS"

AIAA Journal, Vol. 33, No. 8, August 1995, pp. 1383-1390

The interaction between propagating spanwise vortices and a turbulent boundary layer was studied experimentally. The results focus on the relationship between the passage of vortex structures and the response of the boundary layer in terms of ensemble-averaged unsteady mean velocity, wall shear, and turbulent stresses. Both positive and negative circulation vortices were studied at different heights above the test surface. The results indicate that the sign of the vortex influences the wall shear response as well as the height of the vortex above the surface. The negative circulation vortices were found to interact more closely with and penetrate deeper into the boundary layer than the positive sense vortices. A phase lag between the freestream disturbance caused by the vortex and the wall shear stress response is demonstrated. The relationship of the measured wall-shear stress to the pressure gradient and to a scaling velocity determined from the standard log-law fit for the overlap layer are discussed. The response of the boundary-layer turbulence is examined at key phases during the interaction.

Maddalena, L., Vergine, F. and Crisanti, M.

"VORTEX DYNAMICS STUDIES IN SUPERSONIC FLOW: MERGING OF CO-ROTATING STREAMWISE VORTICES"

Physics of Fluids, Vol. 26, 2014, pp. 046101-1 to 046101-17.

For air-breathing propulsion systems intended for flight at very high Mach numbers, combustion is carried out at supersonic velocities and the process is mixing limited. Substantial increase in mixing rates can be obtained by fuel injection strategies centered on generating selected modes of supersonic, streamwise vortex interactions. Despite the recognized importance, and potential of the role of streamwise vortices for supersonic mixing enhancement, only few fundamental studies on their dynamics and interactions have been conducted, leaving the field largely unexplored. A reduced order model that allows the dynamics of complex, interacting, supersonic vortical structures to be investigated, is presented in this work. The prediction of the evolution of mutually interacting streamwise vortices represents an enabling element for the initiation of an effective, systematic experimental study of selected cases of interest, and is an important step toward the design of new fuel injection strategies for supersonic combustors. The case presented in this work is centered on a merging process of co-rotating vortices, and the subsequent evolution of a system composed of two counter-rotating vortex pairs. This interaction was studied, initially, with the proposed model, and was chosen for the peculiarity of the resulting morphology of the vorticity field. These results were used to design an experimental investigation with the intent to target the same specific complex flow physics. The experiment revealed the same peculiar features encountered in the simulation.

Madden, S. J. and Harlan, R. B., editors

"A PROGRAM TO ANALYZE AND MODEL TRAILING VORTICES ON AIRPORTS"

RN-69, October 1971, MIT Measurement Systems Laboratory, Cambridge, MA.

Three specific areas related to the wake turbulence hazard problem are studied. An examination of vortex formation, structure, and decay leads to appropriate mathematical models for use in simulation studies. The effects of atmospheric turbulence and meteorological conditions on the stability and persistence of vortices near the airports are assessed. Development and application of a three-degree-of-freedom computer simulation program provides an understanding of the hazard potential under a variety of encounter situations in which the aircraft, its approach to the vortex, and the vortex strength are varied. Vortex circulation is shown to be the paramount characteristic relating to the hazard potential.

Mager, A.

"SOLUTION ACROSS THE VORTEX BREAKDOWN"

ATR-71 (9999)-1, April 1971, Aerospace Corporation, Los Angeles, CA

The solutions of the quasi-cylindrical, momentum-integral equations for the incompressible, viscous core of a vortex embedded in constant-velocity, axial flow are obtained in a closed form. These

solutions are shown to be discontinuous when the axial flux of the axial momentum deficiency and the circumferential-to-axial velocity ratio at core boundary are larger than certain values. Since the axial gradients on both sides of the discontinuity are shown to be infinite and since the solutions are shown to disappear at one side of the discontinuity, and reappear on the other, vortex breakdown is assumed to occur in the region where the quasi-cylindrical approximation fails to describe the flow. Transition across the vortex breakdown is provided by the connection between the two separated parts of the solution having the same total axial flux of the axial momentum deficiency. The vortex breakdown is conceived as being equivalent to a sudden increase in the dissipation of the swirling motion. No additional constraints are required for the determination of the flow conditions on both sides of the vortex breakdown which indicate a steep increase of the static pressure axis, an enlargement of the core area, and usually, a reversal of the axial flow on the axis.

Mager, A.

"DISSIPATION AND BREAKDOWN OF A WING-TIP VORTEX"

J. Fluid Mech., Vol. 55, Part 4, October 1972, pp. 609-628

The solutions of the incompressible, quasi-cylindrical momentum-integral equations of describing the flow in the viscous core of a wing tip vortex are obtained in a closed form and are shown to have two distinct branches. The discontinuities of these solutions have infinite axial gradients and therefore, following Hall, are assumed to signal the inception of the vortex breakdown. Benjamin's finite transition, with its excess flow force dissipated, is shown to give results equivalent to a sudden cross-over, upstream of the discontinuity, from one branch solution to another. The critical point of such a cross-over is downstream from the cross-over, at the discontinuity. Sarpkaya's experimental data, and the nature of the solutions ahead of the discontinuity, suggest that the physical manifestation of the discontinuity is the spiral breakdown, whereas the cross-over seems to be related to the rapidly expanding and subsequently contracting axisymmetric bubble. This therefore implies that the beginning of the spiral breakdown is the all-important disturbance which triggers off not only the downstream asymmetric departure of the flow from its quasi-cylindrical form but also the formation of the upstream axisymmetric cross-over bubble. Solutions for the turbulent flow downstream from the spiral breakdown indicate that the wing-tip vortex breakdown can result in an appreciable reduction of the maximum circumferential velocity and should thus lessen the danger that trailing vortices present to following aircraft.

Magri, V. and Kalkhoran, I. M.

"NUMERICAL INVESTIGATION OF OBLIQUE SHOCK WAVE/VORTEX INTERACTION"

Computers and Fluids, Vol. 86, 2013, pp. 343-356.

The purpose of the present study was to investigate the interaction between stream-wise vortices with oblique shock fronts of various intensities. A three-dimensional, Navier-Stokes solution of the problem with an orthogonal grid incorporating a RANS approach with a k- ϵ turbulence model was used

to simulate earlier experimental studies of the problem. The accuracy of the computational study was examined by comparing the results to the previous experiments of oblique shock vortex interactions using three different shock wave intensities leading to weak, moderate and strong interactions as identified in our previous experimental investigations. Like the experimental findings, the weak and the moderate interactions did not result in vortex breakdown as the vortex was seen to deflect in the direction of the main flow downstream of the shock with lowered intensity. Computational simulation of the strong interaction case however, confirms presence of a supersonic vortex breakdown having many of the characteristics of subsonic vortex breakdown. The flow field generated by the strong interaction is characterized by the formation of a bulged forward shock structure followed by a rapid expansion of the vortex core, formation of a stagnation point on the vortex axis and appearance of a reversed flow region in a recirculation zone. The vortex was modeled by implementing the experimentally measured vortex properties at the inlet, namely total and static pressures, while constant total temperature was assumed to calculate the velocity, and components of the Mach number. Inlet values for turbulent kinetic energy and turbulent dissipation rate were calculated from assumed values of turbulent intensity.

Mahalingam R. and Komerath, N. M.

"MEASUREMENTS OF THE NEAR WAKE OF A ROTOR IN FORWARD FLIGHT"

AIAA Paper No. 1998-0692, Reno, NV, January 1998

This paper describes initial measurements of the near wake of a 2-bladed teetering, untwisted, square-tipped rotor in forward flight. Issues of periodicity and repeatability of the core are studied using laser velocimetry and flow-visualization on the front of the rotor wake where cycle to cycle variations are expected. Core passage uncertainty from cycle to cycle is less than 1 degree of rotor azimuth. Velocity measurements on the advancing blade side show wake-like core-axial velocities higher than the core circumferential velocity for the first 180 degrees of vortex age. Both the axial and circumferential velocities approach 50% of blade tip speed. The inboard vortex sheet has substantial wake-like velocities and rolls up into a concentrated circulatory region of high wake-like axial velocity rotating opposite to the tip-vortex, within 30 degrees from the blade. The fully-developed values of the vortex core circulation, radius and axial velocity remain constant over 180 degrees of age as current measurements indicate. Measurement on the front, rear and retreating blade side of the rotor are in progress.

Mahalingam, R.

"STRUCTURE OF THE NEAR WAKE OF A ROTOR IN FORWARD FLIGHT AND ITS EFFECT ON SURFACE INTERACTIONS"

PhD Thesis, 1999, Georgia Institute of Technology, Atlanta, GA.

The near wake of a helicopter rotor has a significant role in the aerodynamics, structural dynamics and aeroacoustics of the helicopter. Experiments on a two-bladed rotor in axial flight demonstrate

excellent periodicity and reveal a vortex pairing phenomenon. A quantitative demonstration of periodicity is performed in the wake of a rotor in forward flight. Velocity measurements made at four azimuthal locations in the rotor wake in forward flight indicate strong wake-like axial velocities in the vortex core, comparable to the core circumferential velocity at all azimuthal stations and vortex ages. On the advancing blade side, the inboard wake rolls up into a discrete structure with vorticity close to 40 percent of the tip-vortex, but of opposite sign, and with wake-like axial velocity. Measurements near the blade tip indicate the presence of a strong spanwise flow during the vortex formation process. The evolution of core axial velocity suggests a periodic shedding pattern of rolled-up filaments at the blade tip. It is argued that the decay in core velocities is not related to turbulence in the vortex. The circulation contained in the tip-vortex is only about 40 percent of the peak bound circulation on the rotor blade, computed using the standard assumptions of blade-element theory. Empirical correlation of data from the literature over a wide range of test conditions confirms this finding. This indicates a need to rethink standard methods of blade-element analysis.

Mahalingam, R. and Komerath, N.

"CHARACTERIZATION OF THE NEAR WAKE OF A HELICOPTER ROTOR"

AIAA Paper No. 1998-2909, Albuquerque, NM, June 1998

Vortex characteristics in the near wake of a 2-bladed teetering rotor in steady forward flight are measured using a laser velocimeter. The vortex passage at a measurement point is seen to be repeatable to within 1 degree of rotor revolution. Velocity was measured in planes intersected by the rotor-blade tip at rotor azimuths of 0, 90, 180, 270 degrees. Variations in tip-vortex characteristics such as core radius, circulation and axial velocity were obtained as functions of rotor azimuth and vortex age. The core circulation and core-radius distributions conform to a simple harmonic function of the rotor azimuth. However, the core axial velocity has a fundamental and a 2-per rev variation with rotor azimuth. Empirical curve fits are described for these variations. The core axial velocity is of the order of the peak tangential velocity at all locations. It is higher than the tangential velocity over part of the advancing side of the rotor. The axial velocity is in all cases wake-like, being directed towards the blade of origin. Wake geometries obtained from the LDV data are also presented here.

Mahalingam, R. and Komerath, N.

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rotor azimuth. However, the core axial velocity has a fundamental and a 2-per rev variation with rotor azimuth. Empirical curve fits are described for these variations. The core axial velocity is of the order of the peak tangential velocity at all locations. It is higher than the tangential velocity over part of the advancing side of the rotor. The axial velocity is in all cases wake-like, being directed towards the blade of origin. Wake geometries obtained from the LDV data are also presented here.

Mahalingam, R. and Komerath, N. M.

"ROTOR TIP-VORTEX/AIRFRAME COLLISION FEATURES"

AIAA Paper No. 1996-2013, New Orleans, June 1996

We describe progress towards understanding the basic test case of the interaction between a vortex-dominated wake from a two-bladed rotor, and a solid cylinder surface. The substantial role of the core axial velocity, postulated from pressure data on the airframe, is confirmed by direct velocity measurements. Both the tip vortex core and the inboard vortex sheet, which have opposite signs of vorticity, have substantial wake-like velocities: further evidence that the axial velocity arises from the no-slip condition at the blade edges. Outside the vortex core, there are multiple thin regions of jet-like velocity, attributed to the induced effect of the rolling-up vortex sheets. During the collision, the axial velocity at the top of the airframe persists even after the flow has stagnated on the advancing blade side, further evidence of the blade-wake genesis of this flow. Suction peaks on the retreating blade side stay for a long duration. The levels of suction observed exceed those explainable by potential flow theory.

Mahalingam, R., Funk, R.B. and Komerath, N. M.

"FLOW VISUALIZATION OF LOW-SPEED PERPENDICULAR VORTEX-AIRFOIL INTERACTION"

AIAA Paper No. 1996-2387, June 1996, New Orleans, LA.

The interaction of a wing tip vortex with a downstream airfoil is visualized. The tip vortex from a straight wing was moved vertically in a wind tunnel. Laser sheet videography was used to document the quasi-steady interaction of the vortex with full-span airfoils in two test cases: a 21 percent thick symmetric airfoil, and a thin flat plate of 2.5 percent thickness, with rounded leading edge and sharp trailing edge. The strength of the vortex was computed from the measured velocity profile upstream. Vortex trajectories above and below both airfoils were measured. The vortex filament drifts spanwise above and below the airfoil as expected. During the downstream traverse, the vortex filament stays above the airfoil long after the generating wing has gone below the airfoil and then flips across the airfoil surface in a very short time. The vortex switching from the top to the bottom surface is initiated by the splitting of the primary vortex into two. During the upward traverse, the trajectory is exactly duplicated: there is no delay in switching from below to above, but there is a delay in vortex appearance after switching. Pressure gradient effects are observed in the thick airfoil interaction and near the leading and trailing edges for the flat plate. The trajectories continue to diverge behind the

trailing edge. In both experiments, the remaining vortex filaments downstream of the airfoil are too weak and far apart to recombine.

Mahalingam, R., Funk, R.B. and Komerath, N. M.

"LOW SPEED CANARD-TIP-VORTEX AIRFOIL INTERACTION"

SAE Paper No. 971469, April 1997, Wichita, KS.

This paper describes a series of ongoing experiments to capture the details of perpendicular vortex-airfoil interaction. Three test cases explored are: 1) a 21 percent thick symmetric airfoil at 1.1 deg angle of attack, 2) a thin flat plate of 2.5 percent thickness with rounded leading edge, sharp trailing edge and zero angle of attack and 3) a 12 percent thick symmetric airfoil at zero angle of attack. The tip vortex was generated by a NACA0016 wing at 5 deg AOA. The strength of the vortex was computed from the velocity profile measured upstream for the first two cases. Pressure measurements on the 21 percent airfoil were used to quantify the effect of the vortex as a function of its stand-off distance from the airfoil. Vortex trajectories over the airfoils were obtained from laser sheet videography. The vortex motion conforms to potential flow expectations except in regions of pressure gradient and during head-on interaction. When the generating wing is moved continuously across the airfoil there is a time lag between wing and vortex motion. The vortex switching from the top to the bottom surface is initiated by the splitting of the primary vortex into two and occurs in a short period of time. This is a source of unsteady effects on the interacting airfoil and a vortex jump parameter is defined for the switching process. Issues regarding symmetry in the motion above and below the airfoils are discussed.

Mahalingam, R., Komerath, N. M., Funk, R. B. and Kim, J. M.

"THREE-DIMENSIONAL VORTEX-SURFACE INTERACTIONS"

Seventh Asian Conference on Fluid Dynamics, December 1997, Madras, India.

Vortex-surface interactions of various orientations and relative scales occur in rotorcraft aerodynamics. Basic test cases at high Reynolds number involving cylinders, airfoils and flat plates are used to study the detailed collision processes. The surface pressure distribution is related to the 3-dimensional nature of the vortex-core dynamics, with the core axial velocity playing a crucial role. The phenomena during unsteady cylinder-vortex interaction are summarized. Rapid, oblique vortex-lifting surface interaction causes 3-D separation, alleviated by spanwise flow. Quasi-steady perpendicular vortex/airfoil interaction shows vortex splitting and secondary separation, but no recombination.

Mahalingam, R., Komerath, N. M., Radcliff, T. D., Burggraf, O. R. and Conlisk, A. T.

"VORTEX-SURFACE COLLISION: 3-D CORE FLOW EFFECTS"

AIAA Paper No. 1997-1785, Snowmass Village, CO, June 1997.

The interaction of a strong vortex with a curved surface is a basic problem in fluid mechanics, whose solution is crucial to predicting the flow around a rotorcraft. In past work, the initial stages of the interaction between a rotor tip-vortex and a cylindrical airframe were measured and computed using potential flow concepts followed by boundary layer calculations. This paper presents measurements of the lateral velocity component on the top of the airframe during the vortex interaction. These data are used in the prediction of airframe loading in a time frame far beyond that reported in previous work. The axial velocity in the core of the vortex is substantial and is directed back towards the rotor blade. The vortex core circulation scales with rotor rpm. We show here that the axial velocity plays a major role in the final stages of the collision process. Contours of lateral velocity correspond closely to contours of lateral vorticity from previous work. Core axial velocity during the collision is presented as a function of vortex age. The region of high axial velocity flattens and appears to break in two at the final stages of collision. In the computations, the tip-vortex is modeled as a family of helical vortices, whose strength and initial position are chosen based on experimentally measured core axial velocities. The analytical predictions are compared with experimentally measured vortex propagation and surface pressure.

Mahalingam, R., Wong, O. and Komerath, N.

"EXPERIMENTS ON THE ORIGIN OF TIP-VORTICES"

AIAA Paper No. 2000-0278, Reno, NV, January 2000

Measurements of the structure and evolution of the tip vortex from a rotor in low-speed forward flight are presented. On the advancing blade spanwise flow on the pressure side of the blade is comparable in magnitude to the inflow. Core circumferential velocity profiles show multiple features during formation. Trajectories and peak core velocities of the tip-vortex during its formation on top of the blade are presented. The peak core circumferential velocity is constant during vortex formation. Peak core axial velocity tends towards tip-speed near the blade tip. In the near wake, the variation in core axial velocity exhibits a periodic behavior. Circulation measurements from different rotary-wing tests are correlated with an empirical model that was developed to relate the tip-vortex circulation to the blade parameters. The trailed circulation is seen to be only about 40% of the bound circulation computed using the standard assumptions for calculation of blade loads.

Mahalov, A.

"TURBULENCE AND WAVES IN THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE"

In *Aviation Turbulence*, edited by R. Sharman and T. Lane, Chapter 20, 2016, Springer International Publishing Switzerland, pp. 407-424.

The generation mechanisms and physical characteristics of jet stream turbulence, mountain, and inertia-gravity waves in the upper troposphere and lower stratosphere (UTLS) are investigated for real atmospheric conditions. To resolve multi-scale physical processes of wave breaking and laminated structures in the UTLS region, vertical nesting and adaptive vertical gridding have been developed and

applied in nested, high-resolution, coupled mesoscale-microscale simulations. The fully three-dimensional, moist, compressible Navier-Stokes equations are solved with a stretched, adaptive grid in the vertical and improved resolution in the UTLS region. For verification purposes, real-case simulations are conducted for the Terrain-Induced Rotor Experiment (T-REX) campaign of measurements and selected cases from pilot reports (PIREPs). Comparisons with observational datasets highlight significant benefits of nested computational techniques that consider the shear-stratified turbulence physics of the UTLS. Localized sharp shear layers characterized by stiff gradients of potential temperature and strong alternating vertical velocity patches are resolved in the tropopause region within the embedded microscale nest. We describe fully three-dimensional multi-scale dynamics of laminated structures and nonlinear processes in turbulent layers observed in the UTLS region. Depending on atmospheric conditions, the gravity waves might be trapped at the altitude of the jet stream and break or propagate into higher altitudes acquiring characteristics of inertia-gravity waves. Three-dimensional instabilities in nonparallel shear-stratified flows such as those induced by mountain and polarized inertia-gravity waves in UTLA are characterized by a polarized Richardson number.

Mahesh, K.

"THE INTERACTION OF JETS WITH CROSSFLOW"

Annual Review of Fluid Mechanics, Vol. 45, 2013, pp. 379-407.

It is common for jets of fluid to interact with crossflow. This article reviews our understanding of the physical behavior of this important class of flow in the incompressible and compressible regimes. Experiments have significantly increased in sophistication over the past few decades, and recent experiments provide data on turbulence quantities and scalar mixing. Quantitative data at high speeds are less common, and visualization still forms an important component in estimating penetration and mixing. Simulations have progressed from the Reynolds-averaged methodology to large-eddy and hybrid methodologies. There is a general consensus on the qualitative structure of the flow at low speeds; however, the flow structure at low-velocity ratios (jet speed/crossflow speed) might be fundamentally different from the common notion of shear-layer vortices, counter-rotating vortex pairs, wakes, and horseshoe vortices. Fluid in the near field is strongly accelerated, which affects the jet trajectory, entrainment, and mixing behavior. At low speeds, mixing depends more on Reynolds number than the jet trajectory or spatial extent does. Turbulence kinetic energy budgets are discussed that reveal the considerable nonequilibrium nature of the flow and the consequent challenges posed to time-averaged prediction methodologies. The parameter space at high speeds is large, and even experimentally derived correlations for trajectories show significant scatter. Coherent motions in high-speed jets are seen to entrain large amounts of crossflow fluid but do not mix effectively in the near field.

Mahesh, K.

"A MODEL FOR THE ONSET OF VORTEX BREAKDOWN"

Center for Turbulence Research Annual Research Briefs, 1996, pp. 143-149

A large body of information exists on the breakdown of incompressible streamwise vortices. Less is known about vortex breakdown at high speeds. An interesting example of supersonic vortex breakdown is the breakdown induced by the interaction of vortices with shock waves. The flow in supersonic engine inlets and over high-speed delta wings constitute technologically important examples of this phenomenon, which is termed 'shock-induced vortex breakdown'. In this report, we propose a model to predict the onset of shock-induced vortex breakdown. The proposed model has no adjustable constants, and is compared to both experiment and computation. The model is then extended to consider two other problems: the breakdown of a free compressible vortex, and free incompressible vortex breakdown. The same breakdown criterion is used in all three problems to predict the onset of breakdown. Finally, a new breakdown map is proposed that allows the simultaneous comparison of data from flows ranging from incompressible breakdown to breakdown induced by a shock wave.

Mahesh, K.

"A MODEL FOR THE ONSET OF BREAKDOWN IN AN AXISYMMETRIC COMPRESSIBLE VORTEX"

Physics of Fluids, Vol. 8, No. 12, December 1996, pp. 3338-3345

A simple inviscid model to predict the onset of breakdown in an axisymmetric vortex is proposed. Three problems are considered: the shock-induced breakdown of a compressible vortex, the breakdown of a free compressible vortex, and the breakdown of a free incompressible vortex. The same physical reasoning is used in all three problems to predict the onset of breakdown. It is hypothesized that breakdown is the result of the competing effects of adverse pressure rise and streamwise momentum flux at the vortex centerline. Breakdown is assumed to occur if the pressure rise exceeds the axial momentum flux. A formula with no adjustable constants is derived for the critical swirl number in all three problems. The dependence of the critical swirl number on parameters such as upstream Mach number, excess/deficit in centerline axial velocity, and shock oblique angle is explored. The predictions for the onset of shock-induced breakdown and free incompressible breakdown are compared to experiment and computation, and good agreement is observed. Finally, a new breakdown map is proposed. It is suggested that the adverse pressure rise at the vortex axis be plotted against the axial momentum flux to determine the onset of breakdown. The proposed map allows the simultaneous comparison of data from flows ranging from incompressible breakdown to breakdown induced by a shock wave.

Maines, B. and Arndt, R. E. A.

"THE CASE OF THE SINGING VORTEX"

Journal of Fluids Engineering, Vol. 119, June 1997, pp. 271-276.

A relatively high amplitude, discrete tone is radiated from fully developed tip vortex cavitation under certain conditions. The phenomenon of the 'singing vortex' was first reported by Higuchi et al. (1989).

This study more closely examines the singing phenomenon by varying the hydrofoil cross-section, scale, angle of attack, water quality, and cavitation number in two different facilities. Noise data were collected for each condition with visual documentation using both still photography and high-speed video to explain the mechanism of vortex singing. The theory of Kelvin (1880) provides a framework for correlating all the data obtained.

Majjigi, R. K., Uenishi, K. and Gliebe, P. R.

"AN INVESTIGATION OF COUNTERROTATING TIP VORTEX INTERACTION"

NASA CR-185135, October 1989, GE Aircraft Engines, Cincinnati, OH.

A tip vortex interaction model originally developed for compressors has been extended and adapted for use with counterrotating open rotors. Comparison of available acoustic data with predictions made with and without the tip vortex model included illustrate the importance of this interaction effect. This report documents the analytical modeling, a limited experimental verification, and certain key parametric studies pertaining to the tip vortex as a noise source mechanism for the unsteady loading noise of counterrotating propellers.

Malissa, J. and Ahmad, N. N.

"BOWLES-TATNALL WAKE VORTEX ENCOUNTER HAZARD METRIC"

NASA TM-220285, June 01 2019, NASA Langley Research Center, Hampton, VA.

Wake vortex spacing standards constrict the terminal area throughput and impose severe constraints on the overall capacity and efficiency of the National Airspace System. For more than two decades starting in the early 1990s, the National Aeronautics and Space Administration conducted extensive research on characterizing the formation and evolution of aircraft wakes. This multidisciplinary work included comprehensive field experiments (Pruis et al. 2016), flight tests (Vicroy et al. 1998), and wind tunnel tests (Rossow 1994; Chow et al. 1997). Parametric studies using large eddy simulations (Proctor 1998; Proctor et al. 2006) were conducted to develop fast-time models for the prediction of wake transport and decay (Ahmad et al. 2016). Substantial effort was spent on the formulation of acceptable vortex hazard metrics (Tatnall 1995; Hinton and Tatnall 1997). Several wake encounter severity metrics have been suggested in the past, which include the wake circulation strength, vortex-induced rolling moment coefficient (Clv), bank angle, and the roll control ratio (Tatnall 1995; Hinton and Tatnall 1997; Van der Geest 2012). The vortex-induced rolling moment coefficient introduced by Bowles and Tatnall (Tatnall 1995; Gloudemans et al. 2016) has been used extensively for risk and safety analysis of newly proposed air traffic management concepts and procedures. The original method of Bowles and Tatnall assumed a constant wing loading (the wing lift-curve slope, CL_α is constant), which resulted in an overestimation of the vortex induced rolling moment coefficient. Bowles (2014) suggested a correction to the original method that provides more accurate values of Clv and which is also consistent with the underlying physics of the problem. The overestimation of Clv in

the original method can be corrected by assuming an elliptical lift distribution. Figure 1.1 illustrates the correction in Clv achieved by the modified method.

Malovrh, B. and Gandhi, F.

"SENSITIVITY OF HELICOPTER BLADE-VORTEX-INTERACTION NOISE AND VIBRATION TO INTERACTION PARAMETERS"

Journal of Aircraft, Vol. 42, No. 3, May-June 2005, pp. 685-697

An externally imposed vortex is allowed to interact with a rotor, and the effect of variations in individual key blade-vortex-interaction (BVI) parameters on BVI noise and BVI-induced vibratory hub loading is numerically evaluated. The interaction parameters considered are as follows: 1) vortex strength, 2) vortex core radius, 3) blade-vortex miss-distance, 4) angle of interaction in the blade-shaft plane, 5) angle of interaction in the rotor disk plane (parallel vs oblique interactions), 6) spanwise location of the interaction, 7) spanwise length of the interaction, and 8) blade lift at the time of interaction. The results indicate that an increase in miss distance and interaction angle in the blade-shaft plane and a decrease in the interacting vortex strength are most influential in reducing BVI noise and BVI-induced vibratory hub loading, BVI noise and vibratory hub loading were found to be more sensitive to changes in blade-shaft plane interaction angles than disk plane interaction angles, suggesting that introduction of a modest amount of anhedral/dihedral might be more advantageous than introducing comparable amounts of sweep in the outboard regions of the blade. It is also suggested that vibration reductions obtained for the minimum vibration schedule in the HART test result from an increased interaction angle between the blade and vortex in the blade-shaft plane and have little to do with reduced miss distances.

Maltby, T. L.

"A GENERAL DISCUSSION OF THE DISTURBANCES IN THE WAKE AREA OF A JET AIRCRAFT AND THE EFFECTS OF A SHOCK WAVE INTERCEPTING A SMALL AIRCRAFT"

General Structural Report No. 241, July 1955, Beech Aircraft Corp., Wichita, KS

The purpose of the report is twofold: to investigate the disturbances in the wake area of a jet aircraft that affects the controllability and air loads on a small aircraft entering this region, and to investigate the effect on small aircraft of shock waves generated by supersonic aircraft. The wake area is divided into three areas: the jet engine wake, trailing vortices off the wing tips of the jet aircraft, and residual turbulence.

Mamou, M. and Khalid, M.

"A CFD APPROACH TOWARDS MODELING BLADE/VORTEX IMPINGEMENT EFFECTS AND BUFFETING OVER AIRFOILS"

ICAS-2002-2.5.1, Toronto, Canada, September 2002

Unsteady flows resulting from airfoil-vortex interaction (AVI) and a shockwave-boundary-layer-interaction (SBLI) are studied numerically using the Reynolds averaged Navier-Stokes equations. For the AVI problem, two NACA0012 airfoils are used in tandem. The lead airfoil is used to generate a vortex and the aft one to intercept the vortex and undergoes the AVI process. The interaction of the vortex with the aft airfoil has notable effects upon its aerodynamic characteristics. For the SBLI problem, separated unsteady flows past an 18% thick circular-arc-airfoil and the BGK No. 1 airfoil are studied. The results demonstrated that the unsteady behavior of the flow is sensitive to the turbulence models.

Mandella, M. and Bershader, D.

"QUANTITATIVE STUDY OF THE COMPRESSIBLE VORTEX: GENERATION, STRUCTURE AND INTERACTION WITH AIRFOILS"

AIAA Paper 1987-0328, January 1987, Reno, NV.

Detailed density mappings of shock-generated two-dimensional compressible vortex flow fields have been obtained by the method of pulsed holographic interferometry. The technique of repeated experiments, with sequential advance of time delays for firing the laser light source, provided a time history which included vortex production by an inclined 'generating' airfoil, convection in a quasi-uniform external flow and, finally, interaction with a 'target' airfoil. The measurements included radial density profiles through a single free vortex, supplemented in one case by an independent determination of the radial pressure profile. From these results, an empirical model of the compressible vortex has been developed which includes an extended physical description of its structure. Additionally, experimental results for the earlier transient flow field associated with both leading-edge and trailing-edge vortex generation and development show striking agreement in many details with that obtained by a fluid dynamic computational scheme. Interaction with the downstream target airfoil is characterized by production of a secondary oppositely-rotating vortex which is particularly prominent when the impact is head-on or nearly so. Since the vortex static pressures typically decrease rapidly by a factor of three or more at the center, it is clear that the airfoil interaction produces a substantial transient disturbance to both the lift and drag behavior.

Mangler, K. W. and Smith, J. H. B.

"BEHAVIOR OF THE VORTEX SHEET AT THE TRAILING EDGE OF A LIFTING WING"

Aeronautical Journal, Vol. 74, November 1970, pp. 906-908

The vortex sheet shed from the trailing edge of a lifting wing with non-zero trailing-edge angle, in inviscid subsonic flow, leaves the trailing edge tangentially to the upper or lower surface. However, an exceptional intermediate direction is possible in three circumstances which are discussed in the article.

Mann, J., Cariou, J.-P., Courtney, M. S., Parmentier, R., Mikkelsen, T., Wagner, R., Lindelow, P., Sjöholm, M. and Enevoldsen, K.

"COMPARISON OF 3D TURBULENCE MEASUREMENTS USING THREE STARING WIND LIDARS AND A SONIC ANEMOMETER"

Riso-R-1660(EN), October 2008, Riso National Laboratory for Sustainable Energy, Roskilde, Denmark.

The goal is to compare lidar volume averaged wind measurement with point measurement reference sensors and to demonstrate the feasibility of performing 3D turbulence measurements with lidars. For that purpose three pulsed lidars were used in staring mode, placed so that their beams crossed close to a 3D sonic anemometer mounted at 80 m above the ground. The results show generally very good correlation between the lidar and the sonic times series, except that the variance of the velocity measured by the lidar is attenuated due to spatial filtering. The amount of attenuation can however be predicted theoretically.

Manneville, S., Maurel, A., Bottausci, F. and Petitjeans, P.

"ACOUSTIC CHARACTERIZATION OF A STRETCHED VORTEX IN AN INFINITE MEDIUM"

Lecture Notes in Physics, Vol. 555, 2000, pp. 231-240

A new experimental device is presented, that allows it to isolate and control a stretched vortex in an 'infinite' medium. Acoustic measurements based on the ultrasound-flow interaction yield the main vortex characteristics (position, circulation, core size). This global and non-invasive method also allows a dynamical tracking of the vortex. Experimental results on the mean vortex characteristics as a function of the control parameters are presented, together with some examples of transitory regimes.

Manneville, S., Maurel, A., Roux, P. and Fink, M.

"CHARACTERIZATION OF A LARGE VORTEX USING ACOUSTIC TIME-REVERSAL MIRRORS"

Eur. Physics J. B, Vol. 9, 1999, pp. 545-549

We report new results on the ultrasonic characterization of a fluid flow using an acoustic time-reversal mirror (TRM). The structure of a large vortex generated by a rotating disk in a hollow cylinder is investigated both inside and below the cylinder. For mean-flow characterization, the TRM is shown to be a powerful vorticity detector. Experimental time-of-flight data are successfully compared to a numerical simulation of the flow and the orthoradial velocity is reconstructed using simple geometrical acoustics. Real-time measurements allow us to extract the precession motion of the vortex, providing direct, non-intrusive, and dynamical information on the flow.

Manneville, S., Sandrin, L. and Fink, M.

"INVESTIGATING A STRETCHED VORTEX WITH ULTRAFAST TWO-DIMENSIONAL ULTRASONIC SPECKLE VELOCIMETRY"

Physics of Fluids, Vol. 33, No. 6, June 2001, pp. 1683-1690

Ultrasonic speckle velocimetry (USV) was recently introduced as a new ultrafast tool for measuring fluid velocities in two dimensions by analyzing the speckle signal backscattered from particles moving with the flow. An experimental study of a stationary stretched vortex is presented, which demonstrates the efficiency of ultrafast 2D USV in terms of quantitative assessment of vortical flows. The full velocity field is recovered and compared to the Burgers model for two different fluids: water and milk. The dependence of the vortex characteristics on the main control parameter is investigated.

Mansfield, J. R., Knio, O. M. and Meneveau, C.

"DYNAMIC LES OF COLLIDING VORTEX RINGS USING A 3D VORTEX METHOD"

Journal of Computational Physics, Vol. 152, 1999, pp. 305-345

A Lagrangian particle method is used to simulate the collision of coaxial vortex rings in three dimensions. The scheme combines a 3D, adaptive, viscous, vortex element method with a dynamic eddy viscosity model of the sub-filter scale stresses. The vortex method is based on discretization of the vorticity field into Lagrangian vortex elements and transport of the elements along particle trajectories. The computations incorporate a mesh redistribution algorithm which creates new elements in regions of high strain and locally redistributes the vorticity field into a smaller number of elements when particles tend to cluster. It is shown that the Lagrangian LES scheme captures several experimentally observed features of the ring collisions, including turbulent breakdown into small-scale structures and the generation of small-scale radially propagating vortex rings.

Mantay, W. R., Holbrook, G. T., Campbell, R. L. and Tomaine, R. L.

"FLIGHT INVESTIGATION OF THE RESPONSE OF A HELICOPTER TO THE TRAILING VORTEX OF A FIXED-WING AIRCRAFT"

3rd Atmospheric Flight Mechanics Conf., AIAA, Arlington, TX, June 1976

A flight investigation was conducted to quantitatively determine the response of a medium-weight helicopter to the trailing-vortex system of a fixed-wing aircraft. Flight tests and analytical tools were both utilized in the investigation. The flight tests involved an extensively instrumented UH-1H helicopter and a C-54 aircraft. Penetrations of the vortex system by the UH-1H were made at the following nominal conditions: the C-54 flew at 5500 feet altitude at a nominal gross weight of 58,000 pounds and an indicated airspeed of 115 knots in a cruise configuration. The UH-1H, nominally 7200 pounds gross weight, flew at 60 knots indicated airspeed during the penetrations at separation distances of 6.64 nautical miles to 0.42 nautical miles between aircraft. In general, the data analyzed for the above tests indicated that no unsafe penetration occurred. Further, penetrating vehicle attitude

changes and structural loads were nominal. In addition, the response of the helicopter did not change appreciably with decreased separation distance.

Mantay, W. R., Holbrook, G. T., Campbell, R. L., and Tomaine, R. L.

"HELICOPTER RESPONSE TO AN AIRPLANE'S TRAILING VORTEX"

J. Aircraft, Vol. 14, No. 4, April 1977, pp. 357-363

A flight investigation was conducted to determine quantitatively the response of a medium-weight helicopter to the trailing-vortex system of a fixed-wing aircraft. Both flight tests and analytical tools were utilized in the investigation. The flight tests involved an extensively instrumented UH-1H helicopter and a C-54 aircraft. Penetrations of the vortex system by the UH-1H were made at the following nominal conditions: the C-54 flew at 5500-ft altitude at a nominal gross weight of 58,000 lb and an indicated airspeed of 115 knots in a cruise configuration; the UH-1H, nominally 7200-lb gross weight, flew at 60-knots indicated airspeed during the penetration at separation distances of 6.64 nautical miles to 0.42 nautical mile between aircraft. In general, the data analyzed for these tests indicated that no unsafe penetration occurred. Further, penetrating vehicle attitude changes and structural loads were nominal. In addition, the response of the helicopter did not change appreciably with decreased separation distance.

Mantay, W. R., Shidler, P. A. and Campbell, R. L.

"SOME RESULTS OF THE TESTING OF A FULL-SCALE OGEE-TIP ROTOR"

Journal of Aircraft, Vol. 16, No. 3, March 1979, pp. 215-221.

Full-scale tests were utilized to investigate the effect of the Ogee tip on helicopter rotor acoustics, performance, and loads. Two facilities were used for this study: the Langley whirl tower and a UH-1H helicopter. The test matrix for hover on the whirl tower involved thrust values from 0 to 44,480 N (10,000 lb) at several tip Mach numbers for both standard and Ogee rotors. The full-scale testing on the UH-1H encompassed the major portion of the flight envelope for that aircraft. Both near-field acoustic measurements as well as far-field flyover data were obtained for both the Ogee and standard rotors. Data analysis of the whirl-tower test shows that the Ogee tip does significantly diffuse the tip vortex while providing some improvement in hover performance at moderate thrust coefficients. Flight testing of both rotors indicates that the strong impulsive noise signature of the standard rotor can be reduced with the Ogee rotor. Forward flight performance was significantly improved with the Ogee configuration for moderate lift coefficients. Further, rotor control loads and vibrations were reduced through use of this advanced tip rotor.

Mantay, W. R., Shidler, P. A. and Campbell, R. L.

"SOME RESULTS OF THE TESTING OF FULL SCALE OGEE TIP HELICOPTER ROTOR; ACOUSTICS, LOADS AND PERFORMANCE"

AIAA Paper No. 1977-1340, October 1977, Atlanta, GA.

Full-scale tests were utilized to investigate the effect of the Ogee tip on helicopter rotor acoustics, performance, and loads. Two facilities were used for this study: the Langley whirl tower and a UH-1H helicopter. The test matrix for hover on the whirl tower involved thrust values from 0 to 44,480 N (10,000 lb) at several tip Mach numbers for both standard and Ogee rotors. The full-scale testing on the UH-1H encompassed the major portion of the flight envelope for that aircraft. Both near-field acoustic measurements as well as far-field flyover data were obtained for both the Ogee and standard rotors. Data analysis of the whirl-tower test shows that the Ogee tip does significantly diffuse the tip vortex while providing some improvement in hover performance. Flight testing of both rotors indicates that the strong impulsive noise signature of the standard rotor can be reduced with the Ogee rotor. Forward flight performance was significantly improved with the Ogee configuration for a large number of flight conditions. Further, rotor control loads and vibrations were reduced through use of this advanced tip rotor.

Mantle, P. J.

"INDUCED DRAG OF WINGS IN GROUND EFFECT"

The Aeronautical Journal, Vol. 120, No. 1234, December 2016, pp. 1867-1890.

This paper provides a set of closed form solutions for the lift and drag of wings flying in ground effect both with and without end plates. The developed theories are based on observations of several independent sources of controlled model tests over ground planes and over water and on previous theories prepared by researchers from the original work by Prandtl and Wieselsberger to the present day. The theories developed cover wings of varying aspect ratio, thickness to chord ratios and angle of attack. The results for wings with end plates include the effect of ground (or surface) clearance height, end plate depth and air gap depths beneath the wings or end plates. Good agreement is found between the developed theory and test.

Manuel, G. S., Daryabeigi, Alderfer, D. W. and Obara, C. J.

"IN-FLIGHT OFF-SURFACE FLOW VISUALIZATION USING INFRARED IMAGING"

SAE Paper 91-1006, April 1991, Wichita, KS.

A flight test investigation was conducted to evaluate an infrared (IR) imaging technique to visualize off-surface flow phenomena. A single-engine, general-aviation airplane was equipped with an IR imaging system that viewed the region around the left wingtip. Vortical flow at the wingtip was seeded

with sulfur hexafluoride, a gas with strong infrared absorbing and emitting characteristics. Different terrain and sky backgrounds were evaluated for their effect on IR images of vortical flow. The best IR images were obtained with a clear sky background. The results of the investigation indicate that IR flow visualization compliments existing smoke generator methods for off-surface flow visualization.

Manuel, G. S., Daryabeigi, K., Obara, C. J. and Alderfer, D. W.

"OFF-SURFACE INFRARED FLOW VISUALIZATION"

US Patent 5,200,621, April 1993.

A method for visualizing off-surface flows consists of releasing a gas with infrared absorbing and emitting characteristics into a fluid flow and imaging the flow with an infrared imaging system. This method allows for visualization of off-surface fluid flow in-flight.

Mao, X. and Sherwin, S.

"CONTINUOUS SPECTRA OF THE BATCHELOR VORTEX"

Journal of Fluid Mechanics, Vol. 681, 2011, pp. 1-23.

The spectra of the Batchelor vortex are obtained by discretizing its linearized evolution operator using a modified Chebyshev polynomial approximation at a Reynolds number of 1000 and zero azimuthal wavenumber. Three types of eigenmodes are identified from the spectra: discrete modes, potential modes and free-stream modes. The discrete modes have been extensively documented but the last two modes have received little attention. A convergence study of the spectra and pseudospectra supports the classification that discrete modes correspond to discrete spectra while the other two modes correspond to continuous spectra. Free-stream modes have finite amplitude in the far field whilst potential modes decay to zero in the far field. The free-stream modes are therefore a limiting form of the potential modes when the radial decay rate of velocity components reduces to zero. The radial form of the free-stream modes with axial and radial wavenumbers is investigated and the penetration of the free-stream mode into the vortex core highlights the possibility of interaction between the potential region and the vortex core. A wavepacket pseudo mode study confirms the existence of continuous spectra and predicts the locations and radial wavenumbers of the eigenmodes. The pseudo modes corresponding to the potential modes are observed to be in the form of one or two wavepackets while the free-stream modes are not observed to be in the form of wavepackets.

Mao, X., Sherwin, S. J. and Blackburn, H. M.

"NON-NORMAL DYNAMICS OF TIME-EVOLVING CO-ROTATING VORTEX PAIRS"

Journal of Fluid Mechanics, Vol. 701, 2012, pp. 430-459.

Transient energy growth of disturbances to co-rotating pairs of vortices with axial core flows is investigated in an analysis where vortex core expansion and vortex merging are included by adopting a

time-evolving base flow. The dynamics of pairs are compared with those of individual vortices to highlight the effect of vortex interaction. Three typical vortex pair cases are studied, with the pairs comprised respectively of individually inviscid unstable vortices at the streamwise wavenumber that maximizes the individual instabilities, viscously unstable vortices also at the streamwise wavenumber maximizing the individual instabilities and asymptotically stable vortices at streamwise wavenumber zero. For the inviscidly unstable case, the optimal perturbation takes the form of a superposition of two individual helical unstable modes and the optimal energy growth is like that predicted for an individual inviscid unstable vortex, while where the individual vortices are viscously unstable, the optimal disturbances within each core have similar spatial distributions to the individually stable case. For both cases, time horizons considered are much lower than those required for the merger of the undisturbed vortices. However, for the asymptotically stable case, large linear transient energy growth of optimal perturbations occurs for time horizons corresponding to vortex merging. Linear transient disturbance energy growth exhibited by pairs in this stable case is two to three orders of magnitude larger than that for a corresponding individual vortex. The superposition of the perturbation and the base flow shows that the perturbation has a displacement effect on the vortices in the base flow. Direct numerical simulations of stable pairs seeded by optimal initial perturbations have been carried out and acceleration/delay of vortex merging associated with a dual vortex meandering and vortex breakup related to axially periodic acceleration and delay of vortex merging are observed. For axially invariant cases, the sign of perturbation has an effect, as well as magnitude; the sign dependence relates to whether the perturbation adds to or subtracts from the swirl of the base flow. For a two-dimensional perturbation that adds to the swirl of the base flow, seeding with the linear optimal disturbance at a relative energy level 0.0001 induces the pair to move towards each other and approximately halves the time required for merger. Direct numerical simulation shows that the optimal three-dimensional perturbation can induce the vortex system to break up before merging occurs, since the two-dimensional nature of vortex merging is broken by the development of axially periodic perturbations.

Marais, C.

"PARTICIPATION OF METEO-FRANCE IN WAKE VORTICES STUDIES"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 127-128

To reduce aircraft separation standards defined by ICAO, the French STNA (Service Technique de la Navigation Aérienne) has developed different wake vortices studies. Two studies have been realized by Météo-France. Their goal is to optimize the operations on airports with single or two parallel runways, regarding meteorological conditions and more precisely in case of crosswind. In the first study, a classification of crosswind in terms of wake vortex risk is established using the VORTEX model, developed by CERFACS. This model allows real-time evaluation of hazards associated with the wake vortices (position and strength). The hazard duration is computed; it corresponds to the time the two vortices stay inside the safety corridor. The second study analyzes the evolution of wake vortices at small scale in 2D. This model is initialized with varying academic wind and potential temperatures, based initially on those of the Idaho Falls experiment.

Marchioro, C.

"ON THE INVISCID LIMIT FOR A FLUID WITH A CONCENTRATED VORTICITY"

Comm. in Math. Phys., Vol. 196, 1998, pp. 53-65

We study the time evolution of a viscous incompressible fluid in $\mathbb{R}^2$ when the initial vorticity is sharply concentrated in N regions of diameter ϵ . We prove that in the zero viscosity limit it converges as ϵ vanishes to the inviscid fluid and to the point vortex system.

Marchman, III, J. F.

"WAKE TURBULENCE AND ITS ELIMINATION"

SAE Paper No. 730294, Wichita, KS, 1973

The results of a detailed wind tunnel study of the structure of the trailing vortex to distances of 30 chord lengths downstream of the wing are reported. Five different means of reducing the dangerous high-swirl velocities in a vortex are described and their effects on the wake are illustrated. The effects of these possible vortex 'fixes' on the wing itself as well as the possibility of using these or other devices to accelerate the dissipation of wake turbulence are discussed.

Marchman, III, J. F. and Marshall, J. R.

"VORTEX AGE AS A WAKE TURBULENCE SCALING PARAMETER"

AIAA Paper No. 1974-0036, Washington, DC, 1974

Tests were conducted in the Virginia Tech Stability Wind Tunnel to determine the significance of vortex age as a scaling parameter in wake turbulence development and dissipation. Vortex structure was measured over a range of three angles of attack, three free-stream speeds, and seven downstream positions from 2 to 30 chord lengths using an NACA 0012 wing and a five-hole yaw head probe. The resulting data indicates that vortex age is not a self-sufficient scaling parameter but a free-stream velocity influence also exists at higher angles of attack which cannot be explained in terms of Re or M .

Marchman, III, J. F. and Uzel, J. N.

"EFFECT OF SEVERAL WING TIP MODIFICATIONS ON A TRAILING VORTEX"

J. Aircraft, Vol. 9, No. 9, September 1972, pp. 684-686

Several different wing-tip modifications were used to alter the characteristics of an airfoil trailing vortex. Preliminary photographs were taken using a tuft-grid to visually determine the effects of the

various tip configurations. Detailed mean flow measurements were then made at ten and thirty chord lengths downstream of the wing. As a first approximation, the static pressure was assumed to be constant. The results show a definite decrease in the tangential velocity of the vortex and a spreading out of the core for all modifications tested.

Marchman, III, J. F., Manor, D. and Faery, Jr., H. F.

"WHITCOMB WINGLET APPLICATIONS TO GENERAL AVIATION AIRCRAFT"

AIAA Paper No. 1978-1478, Los Angeles, CA, August 1978

A study was conducted to examine several of the aspects of Whitcomb winglet applications to low speed, general aviation aircraft. Both supercritical and laminar flow airfoil section winglets were tested on straight and tapered symmetrical wings. Aerodynamic parameters were measured for a wide range of wing angles of attack and for several winglet angles. Tests were run to determine the low-speed effect of the wing on the winglet and of the winglets on the wing. Towing tank and wind tunnel tests were run to examine the trailing vortices from the wing-winglets combinations. The tests showed that winglets are effective at low speeds, however a tapered wing planform results in a reduction of the winglet effectiveness. Symmetrical winglets were shown to be effective at low speed. Tests also indicated that a proper choice of winglet angle can reduce the strength of the wing wake turbulence.

Marcu, B., Meiburg, E. and Newton, P. K.

"DYNAMICS OF HEAVY PARTICLES IN A BURGERS VORTEX"

Physics of Fluids, Vol. 7, No. 2, February 1995, pp. 400-410.

This paper presents a linear stability analysis as well as some numerical results for the motion of heavy particles in the flow field of a Burgers vortex, under the combined effects of particle inertia, Stokes drag, and gravity. By rendering the particle motion equations dimensionless, the particle Stokes number, a Froude number, and a vortex Reynolds number are obtained as the governing three parameters. In the absence of gravity, the vortex center represents a stable equilibrium point for particles up to a critical value of the Stokes number, as the inward drag overcomes the destabilizing centrifugal force on the particle. Particles exceeding the critical Stokes number value asymptotically approach closed circular orbits. Under the influence of gravity, one or three equilibrium points appear away from the vortex center. Both their locations and their stability characteristics are derived analytically. These stability characteristics can furthermore be related to the nature of the critical points in a related directional force field. These findings are expected to be applicable to the coupling between the small-scale turbulent flow structures and the motion of suspended particles.

Marcus, D. L. and Berger, S. A.

"THE INTERACTION BETWEEN A COUNTER-ROTATING VORTEX PAIR IN VERTICAL ASCENT AND A FREE SURFACE"

Phys. Fluids A, Vol. 1, No. 12, December 1989, pp. 1988-2000

The inviscid, two-dimensional interaction between a pair of counter-rotating line vortices and a free surface has been studied. A solution to the linearized, small-disturbance problem has been thoroughly explored. For the nonlinear problem numerical calculations were carried out for Froude numbers representing a range of very weak to very strong vortices. Strong vortices are little affected by the presence of the surface, rising to form a bubblelike disturbance; weaker vortices follow paths like vortices approaching a plane boundary. The experimentally observed scarring phenomena - surface depressions whose axes are perpendicular to the flow plane - are seen in the numerical results.

Margaris, P. and Gursul, I.

"EFFECT OF STEADY BLOWING ON WING TIP FLOWFIELD"

AIAA Paper No. 2004-2619, Portland, OR, June-July 2004

An experimental investigation was conducted to study the effect of steady blowing near the wing tip, as a means of control of the trailing vortex. Velocity measurements were taken, using a PIV system, around the tip and in the near wake of a rectangular wing, which was equipped with several blowing slots. The results show that the effect of blowing is very sensitive to the blowing configuration. The location and strength of the vortices generated by the jet and their interaction with the tip vortex may lead to a diffused trailing vortex or an even more coherent one. Spanwise blowing generally leads to a diffused trailing vortex, unless it is applied very close to the suction surface of the wing, for which a much stronger vortex is generated. Blowing in the vertical direction produces multiple co-rotating vortices with increasing blowing coefficient. Diffused or stronger vortices are generated, depending on the direction of the vertical blowing. Finally, the instantaneous data derived from the PIV measurements show differences with the time-averaged measurements and reveal several differing phenomena in the flowfield.

Margaris, P. and Gursul, I.

"VORTEX TOPOLOGY OF WING TIP BLOWING"

Aerospace Science and Technology, Vol. 14, 2010, pp. 143-160.

An extensive parametric study was conducted to examine the effect of continuous blowing from high aspect ratio jets on the tip vortex in the near wake. It was found that the high aspect ratio jet produces a pair of counter-rotating vortices of unequal strength; their interaction with the tip vortex leads to single or multiple-vortex wakes. The flow topology of the wake depends on several parameters such as the blowing configuration, the blowing coefficient, and the wing incidence. Vertical and spanwise blowing were examined, from different vertical and longitudinal positions. In most cases, blowing from near the pressure surface led to diffused vortices in the near wake with blowing from near the suction surface producing the opposite effect. The tip shape was also varied; the round tip showed the ability to promote the Coanda effect, thus modifying the vortex interaction. The wing incidence was found to affect not only the tip vortex, but also the jet-generated vortices.

Margaris, P. and Gursul, I.

"WING TIP VORTEX CONTROL USING SYNTHETIC JETS"

Aeronautical Journal, October 2006, pp. 673-681

An experimental investigation was conducted to study the effect of synthetic jet (oscillatory, zero net mass flow jet) blowing near the wing tip, as a means of diffusing the trailing vortex. Velocity measurements were taken, using a Particle Image Velocimetry system, around the tip and in the near wake of a rectangular wing, which was equipped with several blowing slots. The effect of the synthetic jet was compared to that of a continuous jet blowing from the same configurations. The results show that the use of synthetic jet blowing is generally beneficial in diffusing the trailing vortex and comparable to the use of continuous jet. The effect was more pronounced for the highest blowing coefficient used. The driving frequency of the jet did not generally prove to be a significant parameter. Finally, the instantaneous and the phase-locked velocity measurements helped explain the different mechanisms employed by the continuous and synthetic jets in diffusing the trailing vortex.

Margaris, P. and Gursul, I.

"VORTEX TOPOLOGY OF WING TIP BLOWING"

AIAA Paper No. 2007-1122, Reno, NV, January 2007

An experimental investigation was conducted to study the effect of continuous blowing from high aspect ratio jets near the tip-on-tip vortex in the near wake. This study followed a previous study and focused on the effect of two new parameters: the shape of the tip and the longitudinal position of the blowing slot. Velocity measurements were taken, using a PIV system, around the tip and in the near wake of a rectangular wing, which was equipped with several blowing slots. The effect was compared to that of the previous study. The results showed that the tip shape is an important parameter, influencing the formation and characteristics of the tip vortex and thus leading to different flowfields in the near wake. Depending on the blowing configuration, a round tip can lead to a more diffused trailing vortex or to multiple coherent vortices, stronger than those produced by a square tip. The round tip also promotes the Coanda effect, which influences the structure of the vortex. The longitudinal position of the blowing slot is also an important parameter. It does not change the general topology of the near wake but when the blowing slot is located further downstream it retains more of its velocity leading to higher crossflow velocities in the near wake.

Margaris, P., Marles, D. and Gursul, I.

"EXPERIMENTS ON INTERACTION OF A JET WITH A TRAILING VORTEX"

AIAA Paper No. 2007-1123, Reno, NV, January 2007

A parametric study was performed to evaluate the effect of a cold jet on a single trailing vortex. Flow visualization and Particle Image Velocimetry (PIV) measurements were conducted in wind and water tunnels. The main parameters examined were the ratio of jet strength to vortex strength, the initial distance between the jet and the vortex, the jet inclination angle, the Reynolds number, and the downstream distance from the trailing edge. It was shown that the jet turbulence is wrapped around the vortex and ingested into it with increasing streamwise distance. This turbulence ingestion takes place faster with decreasing jet-to-vortex distance and increasing jet strength. Both time-averaged and instantaneous flow fields showed that the effect of the jet on the vortex can be quite significant. The trailing vortex became diffused with its rotational velocity and vorticity levels reduced. The mechanism with which the jet interacts with the vortex is a combination of vortices shed by the jet and the turbulence. No noticeable differences were found within the Reynolds number range tested. The effect of jet on vortex is delayed when the jet is blowing at an angle to the free stream and away from the vortex such as during take-off. The results suggest that the engine jets might have favorable effects on wing vortices, in particular on flap-edge vortices.

Margaris, P., Marles, D. and Gursul, I.

"EXPERIMENTS ON JET/VORTEX INTERACTION"

Electrorheological Fluids, Vol. 44, No. 2, Feb. 2008, pp. 261-278

An experimental study was performed to conduct a parametric study of the effect of a cold jet on a single vortex. Flow visualization and Particle Image Velocimetry (PIV) measurements were conducted in wind and water tunnels. The main parameters that were examined were the ratio of jet strength to vortex strength, the initial distance between the jet and the vortex, the jet inclination angle, the Reynolds number, and the downstream distance from the trailing edge. It was shown that the jet turbulence is wrapped around the vortex and ingested into it with increasing streamwise distance. This turbulence ingestion takes place faster with decreasing jet-to-vortex distance and increasing jet strength. Both time-averaged and instantaneous flow fields showed that the effect of the jet on the vortex can be quite significant. The trailing vortex got diffused with its rotational velocity and vorticity levels reduced. Some signs of decay were also found (small reduction in total circulation and cross-flow kinetic energy) for small jet to vortex distance and high jet strength. The mechanism with which the jet interacts with the vortex is a combination of vortices shed by the jet and the turbulence. No noticeable differences were found within the Reynolds number range tested. The effect of jet on vortex is delayed when the jet is blowing at an angle to the free stream and away from the vortex such as during take-off. The results suggest that the engine jets might have favorable effects on wing vortices, in particular on flap-edge vortices.

Margaris, P., Marles, D. and Gursul, I.

"EXPERIMENTS ON JET/VORTEX INTERACTION"

Experiments in Fluids, Vol. 44, 2008, pp. 261-278

An experimental study was performed to evaluate the effect of a cold jet on a single trailing vortex. Flow visualization and particle image velocimetry (PIV) measurements were conducted in wind and water tunnels. The main parameters were the ratio of jet-to-vortex strength, the jet-to-vortex distance, the jet inclination angle, and the Reynolds number. It was shown that the jet turbulence is wrapped around the vortex and ingested into it. This takes place faster with decreasing jet-to-vortex distance and increasing jet strength. Both time-averaged and instantaneous flow fields showed that the trailing vortex became diffused with its rotational velocity and vorticity levels reduced when the jet is located close to the vortex. The mechanism with which the jet interacts with the vortex is a combination of vortices shed by the jet and the turbulence. No noticeable differences were found within the Reynolds number range tested. The effect of jet on the vortex is delayed when the jet is blowing at an angle to the free stream and away from the vortex such as during take-off.

Margerit, D.

"THE COMPLETE FIRST ORDER EXPANSION OF A SLENDER VORTEX RING"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany, pp. 45-53.

Equations for the axisymmetric part of the velocity field and for the equation of motion of a non circular slender vortex ring are given at first order. This is the correction to the known leading order given by Callegari and Ting.

Margerit, D. and Brancher, J.-P.

"ASYMPTOTIC EXPANSIONS OF THE BIOT-SAVART LAW FOR A SLENDER VORTEX WITH CORE VARIATION"

J. Engineering Mathematics, Vol. 40, 2001, pp. 297-313

The Method of Matched Asymptotic Expansion of Singular Integrals is used to expand the Biot-Savart law in terms of different parameters. This method is first used to find, in terms of the small distance r to a line vortex, the first orders of the known expansion of the potential flow induced by this line vortex. This method is also used to easily compare two equations of motion of a slender vortex filament: the one obtained in an ad-hoc way by a cut-off line-integral technique and the other derived from the Navier-Stokes equations by Callegari and Ting. Finally, this method is used to give the inner expansion of the flow induced by a slender vortex in terms of its slenderness. This is the first inner expansion up to order one in terms of ϵ of the Biot-Savart law for a slender vortex. An application of this inner expansion is then given to find the induced velocity of a family of non-circular vortex rings with axisymmetric axial-core variation.

Margerit, D., Brancher, P. and Giovannini, A.

"IMPLEMENTATION AND VALIDATION OF A SLENDER VORTEX FILAMENT CODE: ITS APPLICATION TO THE STUDY OF A FOUR-VORTEX WAKE MODEL"

International J. for Numerical Methods in Fluids, Vol. 44, January 2004, pp. 175-196

A computational code EZ-vortex is developed for the motion of slender vortex filaments of closed or open shape. The integro-differential equations governing the motion of the vortex centerlines are either the Callegari and Ting equations, which are the leading order solution of a matched asymptotic analysis, or equivalent forms of these equations. They include large axial velocity and nonsimilar profiles in the vortical cores. The fluid may be viscous or inviscid. This code is validated both against known solutions of these equations and results from linear stability analyses. The linear and non-linear stages of a perturbed two-vortex wake and of a four-vortex wake model are then computed.

Marichal, Y., De Visscher, I., Chatelain, P. and Winckelmans, G.

"IDENTIFICATION AND QUANTIFICATION OF VORTICAL STRUCTURES IN WIND TURBINE WAKES FOR OPERATIONAL WAKE MODELING"

The Science of Making Torque from Wind (TORQUE 2016), published in IOP Journal of Physics: Conference Series Vol. 753, 2016, pp. 032050-1 to 032050-11.

The present paper describes a method to quantify the vortical structure characteristics from simulation results of the flow past a wind turbine with the aim to develop an accurate, physics-based operational wake model. The wake centerline is first identified. Then, the flow characteristics are extracted by fitting a vorticity-based wake skeleton onto the velocity deficit profiles defined around the centerline and measured at several downstream distances from the rotor. The simulation results were obtained using a hybrid Vortex Particle-Mesh approach combined with an immersed Lifting Line technique to account for the blades. The characterization of the identified vortex wake structure lays a basis for the development of an operational wake model based on strong physical grounds.

Marks, P.

"OUT OF THE VORTEX"

New Scientist, Vol. 167, No. 2248, 22 July 2000, p. 4

A pair of engineers from Boeing have patented a way of stifling deadly vortices. As well as making flying safer, it promises to ease congestion at busy airports by reducing the gap between planes as they land.

Marks, T. and Gollnick, V.

"INFLUENCE OF AIRCRAFT TYPE AND ORDER ON FUEL SAVINGS GAINED BY TWO-AIRCRAFT FORMATIONS"

ICAS-2016-0592, September 2016, Daejeon, Korea.

The work presented in this paper investigates the influence of aircraft pairing and order on the fuel savings gained by two-aircraft formations. It will be analyzed if in terms of formation efficiency as well as with respect to the maximum fuel savings favorable aircraft pairings exist. To achieve this goal, a detailed trajectory analysis including an aerodynamic model to calculate the aerodynamic benefits of the formation is performed for a predefined set of formation geometries and formation pairings thus creating a formation flight database that can be used for the evaluation. It will be shown by statistical analysis, that differences in formation flight performance exist depending on pairing and order. In addition to the full initial set of samples a subset of the formation geometries representing missions over the North Atlantic will be evaluated. It will be shown, that differences compared to the full set of samples exist. As the weight of the leader is a strong driver for the formation efficiency it will be analyzed, if the take-off weights of the formation members allow an estimation of the achievable benefits. Furthermore, it will be shown, how the database can be used to create surrogate models for a specific formation pairing and how these models can be utilized to evaluate specific formation geometries.

Marles, D. and Gursul, I.

"EFFECT OF A JET ON VORTEX MERGING"

AIAA Paper 2007-4364, June 2007, Miami, FL.

Experiments were conducted to understand the effect of an axial jet on the merging process of a simulated flap-edge and wing-tip co-rotating vortex pair in the near wake. Cross-flow velocity measurements and flow visualization were performed for three realistic jet positions on both equal and unequal strength like-signed vortices for a range of momentum coefficients. The main finding was that the initial jet position has a vastly contrasting effect on the merging process. If the jet turbulence interacts rapidly with only one of the vortices, severe diffusion of that vortex occurs which ultimately wraps around and becomes consumed by the unaffected vortex structure. The jet causes a reduction in the vortex spacing and an increase in the rotation angle, hence merging is promoted. If the jet turbulence does not interact directly with either vortex, but instead interferes with the mechanism in the outer-recirculation region that advects vorticity to a larger radius, then merging can be retarded. In this case, an increase in vortex spacing and reduction in rotation angle was observed. Increasing the momentum coefficient, hence introducing more turbulence into the flow, has a greater effect on the merging process.

Marles, D. and Gursul, I.

"EFFECT OF AN AXIAL JET ON VORTEX MERGING"

Physics of Fluids, Vol. 20, 2008, pp. 047101-1 - 047101-16.

Experiments were conducted to understand the effect of an axial jet on the merging process of a simulated flap-edge and wing-tip co-rotating vortex pair in the near wake. Cross-flow velocity measurements and flow visualization were performed for three realistic jet positions on both equal and

unequal strength like-signed vortices for a range of momentum coefficients. The main finding was that the initial jet position has a vastly contrasting effect on the merging process. If the jet turbulence interacts rapidly with only one of the vortices, severe diffusion of that vortex occurs which ultimately wraps around and becomes consumed by the unaffected vortex structure. The jet causes a reduction in the vortex spacing and an increase in the rotation angle, hence merging is promoted. If the jet turbulence does not interact directly with either vortex, but instead interferes with the mechanism in the outer-recirculation region that advects vorticity to a larger radius, then merging can be retarded. In this case, an increase in vortex spacing and reduction in rotation angle was observed. Increasing the momentum coefficient, hence introducing more turbulence into the flow, has a greater effect on the merging process.

Marles, D. Margaris, P. and Gursul, I.

"EFFECT OF AN AXIAL JET ON AIRCRAFT WAKE VORTICES"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

The effects of an axial jet on trailing vortices were investigated experimentally. To simulate various configurations of aircraft wake vortices, experiments were performed with single vortices, co-rotating vortex pairs, and counter-rotating vortex pairs generated by rectangular wings. Flow visualization and PIV measurements were conducted in wind and water tunnels. For a single trailing vortex, the main parameters were the ratio of jet-to-vortex distance, the jet inclination angle, and the Reynolds number. It was shown that the jet turbulence is wrapped around the vortex and ingested into it. This takes place faster with decreasing jet-to-vortex distance and increasing jet strength. Both time-averaged and instantaneous flow fields showed that the trailing vortex became diffused with its rotational velocity and vorticity levels reduced when the jet was located close to the vortex. The mechanism with which the jet interacts with the vortex is a combination of vortices shed by the jet and the turbulence. No noticeable differences were found within the Reynolds number range tested. The effect of jet on the vortex is delayed when the jet is blowing at an angle to the free stream and away from the vortex such as during take-off. For a co-rotating vortex pair, which simulates flap-edge and wing-tip vortices in the near wake, cross-flow velocity measurements and flow visualization were performed. These experiments included three realistic jet positions on both equal and unequal strength like-signed vortices for a range of momentum coefficients. The main finding was that the initial jet position has a vastly contrasting effect on the merging process. If the jet turbulence interacts rapidly with only one of the vortices, severe diffusion of that vortex occurs which ultimately wraps around and becomes consumed by the unaffected vortex structure. The jet causes a reduction in the vortex spacing and an increase in the rotation angle, hence merging is promoted. If the jet turbulence does not interact directly with either vortex, but instead interferes with the mechanism in the outer-recirculation region that advects vorticity to a larger radius, then merging is retarded. In this case, an increase in vortex spacing and reduction in rotation angle was observed. Increasing the momentum coefficient, hence introducing more turbulence into the flow, has a greater effect on the merging process.

Marsh, D.

"MASS MOMENT OF INERTIA ESTIMATION METHODS -- MANNED AIRCRAFT"

21st National Conference, Society of Aeronautical Weight Engineers, May 1962, Seattle, WA.

The purpose of this paper is to furnish the engineer with a method for rapidly and accurately estimating the moment of inertia of manned aircraft during the advanced design period. Such inertias are needed so that dynamic load and stability characteristics of the aircraft may be evaluated. To evolve a method which would not be limited to any particular type of aircraft, empirical data were gathered from many types of combat and transport aircraft and combined with the results of a mass distribution parametric study. By this method, the moment of inertia for a complete aircraft can be computed with a total expended time of about three man-hours. The prerequisite data needed are a group weight and balance statement, a three-view drawing, and some knowledge of the design characteristics of the airplane. As with all procedures and methods based on empirical data, extrapolations by this method are limited to aircraft within the present state of the art. As advancements in the state of the art occur which significantly affect aircraft weight distribution, the method should be altered accordingly.

Marsh, D. P.

"MASS MOMENT OF INERTIA ESTIMATION METHODS - MANNED AIRCRAFT"

Society of Allied Weight Engineers, Inc., 21st National Conference, May 1962, Seattle, WA.

This paper was presented at the Twenty-first Annual National Conference of the Society of Aeronautical Weight Engineers at Seattle, Washington, May 14-17, 1962. The purpose of this paper is to furnish the engineer with a method for rapidly and accurately estimating the moment of inertia of manned aircraft during the advanced design period. Such inertias are needed so that dynamic load and stability characteristics of the aircraft may be evaluated.

Marshall, J. R. and Marchman III, J. F.

"VORTEX AGE AS A WAKE TURBULENCE SCALING PARAMETER"

NASA CR-132312 (VPI-AERO-006), August 1973, Virginia Polytechnic Institute and State University, Blacksburg, VA.

A program of research was conducted in the Virginia Tech Stability Wind Tunnel to determine the significance of vortex age as a scaling parameter in wake turbulence development and dissipation. Tests were conducted at three angles of attack, three free stream speeds, and seven downstream positions from 2 to 30 chord lengths using an NACA 0012 wing and a five hole yawhead pitot probe. The end surface of the wing tip was flat. Speeds were selected to give a predetermined range of vortex ages. The complete velocity structure of the vortex was measured at each station and speed. The resulting plots of maximum tangential velocity and vortex core diameter versus downstream distance and vortex age indicate that vortex age is not a self-sufficient scaling parameter. In addition to the expected effect

of lift coefficient there is also a definite free stream speed influence at high wing angles of attack. The exact cause and nature of this effect is not fully understood, but it does not appear to be explainable in terms of Mach number or Reynolds number; however, the influence of tip edge shape on spanwise flow separation appears to be an important factor.

Marshall, J. S.

"PARTICLE DISPERSION IN A TURBULENT VORTEX CORE"

Physics of Fluids, Vol. 17, No. 2, Feb. 2005, pp. 025104-1 to 025104-15

A study is performed using direct numerical simulation to examine the effect of turbulence on particle dispersion in a columnar vortex. A procedure is used to generate initial conditions in which turbulence external to the vortex has the wrapped, nearly azimuthal form characteristic of turbulence around a large-scale vortex structure. This approach enables control of the initial values of the external turbulence intensity and length scale for a given vortex size and strength. The effect of turbulence on dispersion of particles by the vortex flow is examined for a wide range of different values of the initial turbulence intensity. Cases both with zero mean axial flow and unstable vortices with nonzero mean axial flow are examined. The state of the external turbulence is determined by a balance between dissipation, stretching, and vorticity reorientation and stripping from the large-scale vortex core. We examine cases with peak initial turbulence kinetic energy differing by a ratio of up to 400, and for all cases we observe that the external turbulence has a dramatic effect on the particle dispersion. The results of the study have implications for large-eddy simulation of particulate flows for which the particle concentration in the region surrounding the coherent vortex structures will not be accurately predicted if the effect of smaller-scale turbulence surrounding these structures on particle dispersion is not resolved or appropriately modeled.

Marshall, J. S.

"THE FLOW INDUCED BY PERIODIC VORTEX RINGS WRAPPED AROUND A COLUMNAR VORTEX CORE"

J. Fluid Mech., Vol. 345, 1997, pp. 1-30

A study has been performed of the interaction of periodic vortex rings with a central columnar vortex, both for the case of identical vortex rings and the case of rings of alternating sign. Numerical calculations, both based on an adaptation of the Lundgren-Ashurst (1989) model for the columnar vortex dynamics and by numerical solution of the axisymmetric Navier-Stokes and Euler equations in the vorticity-velocity formulation using a viscous vorticity collocation method, are used to investigate the response of the columnar vortex to the ring-induced velocity field. In all cases, waves of variable core radius are observed to build up on the columnar vortex core due to the periodic axial straining and compression exerted by the vortex rings. For sufficiently weak vortex rings, the forcing by the rings serves primarily to set an initial value for the axial velocity, after which the columnar vortex waves oscillate approximately as free-standing waves. For the case of identical rings, the columnar vortex waves exhibit a slow upstream propagation due to the nonlinear forcing. The cores of the vortex rings

can also become unstable due to the straining flow induced by the other vortex rings when the ring spacing is sufficiently small. This instability causes the ring vorticity to spread out into a sheath surrounding the columnar vortex. For the case of rings of alternating sign, the wave in core radius of the columnar vortex becomes progressively narrower with time as rings of opposite sign approach each other. Strong vortex rings cause the waves on the columnar vortex to grow until they form a sharp cusp at the crest, after which an abrupt ejection of vorticity from the columnar vortex is observed.

Marshall, J. S.

"CROSS-STREAM VORTICITY FIELD INDUCED BY STREAMWISE VORTICES IN UNBOUNDED AND WALL-BOUNDED SHEAR FLOWS"

Theoretical and Computational Fluid Dynamics, Vol. 16, 2003, pp. 231-247.

This computational study examines the unsteady cross-stream vorticity structures that form when one or more streamwise vortices are immersed in homogeneous and boundary-layer shear flows. A quasi-two-dimensional limit is considered in which the velocity and vorticity fields, while still possessing three nonzero components, have vanishing gradient in the streamwise direction. This idealization is suitable to applications such as streamwise vortices that occur along a ship hull or airplane fuselage and it can be used as an idealized representation of the quasi-streamwise vortices in the near-wall region of a turbulent boundary layer. In this quasi-two-dimensional idealization, the streamwise velocity has no effect on the cross-stream velocity associated with the vortex. However, the vortex acts to modify the cross-stream vorticity component, resulting in regions of the flow with strong deviations in streamwise velocity. This paper examines the complex structures that form as the cross-stream vorticity field is wrapped up by the vortex and the effect of these structures on the streamwise velocity field, first for vortices immersed in homogeneous shear flow and then for vortices immersed in a boundary layer along a flat wall.

Marshall, J. S.

"BUCKLING OF A COLUMNAR VORTEX"

Physics of Fluids A, Vol. 4, No. 12, December 1992, pp. 2620-2627.

The instability of a columnar vortex under axial compression is studied analytically. Prediction of the change with time of an initial perturbation in the form of a small-amplitude helical wave on the vortex core is reduced to solution of a system of two linear, second-order ordinary differential equations. For small rates of compression, a closed-form asymptotic solution of these equations is obtained using a two-variable expansion in time. The results indicate that a vortex under compression may bend (or 'buckle') or it may remain columnar with an increase in core radius. The choice of which of these possible outcomes will occur is found to depend on the value of a single dimensionless parameter given by the product of the wave number k of the helical perturbation and the radius r of the vortex core. Where kr is greater than a critical value, found to be approximately 1.77, the perturbation amplitude will decrease with axial compression and no 'buckling' will occur. When kr is less than this critical value,

the perturbation amplitude will increase as the vortex axis is compressed and 'buckling' will be observed.

Marshall, J. S.

"VORTEX CUTTING BY A BLADE, PART I: GENERAL THEORY AND A SIMPLE SOLUTION"

AIAA Journal, Vol. 32, No. 6, June 1994, pp. 1145-1150.

A simplified theory for long-wave motion of vortex filaments with variable core radius is given, for small values of the ratio $e = \max(a/L)$ of core radius a to axial length scale L , which offers a number of advantages for numerical computations of the vortex response. An analytical solution of this theory is then obtained for the axial flow within a straight vortex filament following cutting of the vortex by a flat blade at an angle of attack α . The mathematical structure of the solution is like the classic problem of impulsive piston motion in a shock tube, and analogies of shocks and expansion waves propagating on the vortex away from the blade are predicted. A simple expression for the vortex force on the blade is derived, which is found to be mainly dependent on the ratio of the vortex core radii on opposing sides of the blade.

Marshall, J. S.

"MODELS OF SECONDARY VORTICITY EVOLUTION DURING NORMAL VORTEX-CYLINDER INTERACTION"

AIAA Journal, Vol. 40, No. 1, January 2002, pp. 170-172

A generic experimental setup was used to study the secondary vorticity produced during vortex-body interaction. The study is believed to have implications on a broad class of problems involving vortices interacting with helicopter rotor, or marine propeller blades and control surfaces. Analytical models are presented for aspects of the flow observed during normal interaction of a columnar vortex and a circular cylinder, including onset of outward ejection of secondary vorticity from the cylinder boundary layer and variation of the strength of the ensuing vortex loop as a function of time and position along the loop.

Marshall, J. S.

"EFFECT OF PARTICLE COLLISIONS ON THE EXPULSION OF HEAVY PARTICLES FROM A VORTEX CORE"

Physics of Fluids, Vol. 18, 2006, pp. 113301-1-113301-12

A computational study has been performed on the effect of particle collisions as heavy particles are expelled from a vortex core. In the absence of collisions, particles collect in a band surrounding the vortex core, where the maximum particle concentration within this band increases indefinitely as the band of particles propagates radially outward. Particle collisions act to regulate the increase in concentration within this band by the enhanced spreading of the particles that occurs through the action of shear-induced migration. The presence of axial flow within the vortex core introduces a drift

of the particles within the core toward the low-shear region at the core center, thus resisting the outward particle drift caused by centrifugal force. With increasing axial flow rates, the particles are retained in the vortex core for longer time periods. The role of various parameters on the particle expulsion is evaluated, including particle diameter, restitution coefficient, and initial concentration. The study also examines the effect of collisions on cases with two distinct particle sizes, in which the different outward expulsion rates act to separate particles of different size.

Marshall, J. S.

"RESPONSE OF A COLUMNAR VORTEX TO A WRAPPED VORTEX LOOP"

ESAIM Proceedings, Vol. 7, 1999, pp. 280-291.

A computational and experimental study of the interaction between an initially columnar vortex and a wrapped vortex loop was performed, which focused on the columnar vortex response to the vortex loop. This problem is motivated by applications involving three-dimensional vortex interaction with a solid body, where the secondary vorticity shed from the body rolls up into a series of loop-like structures that are advected away from the body by the primary vortex. As a secondary vortex loop wraps around a columnar vortex, it becomes entrained into the vortex core due to the self-induced velocity of the loop. The columnar vortex response as a secondary vortex loop moves close to and impacts upon its lateral core surface includes a combination of bending waves, waves of variable core area, and core shape deformation. If a vortex loop is sufficiently strong, its interaction with the columnar vortex is also accompanied by ejection of vorticity from the columnar vortex, sometimes leading to development of a traveling vortex breakdown.

Marshall, J. S. and Chen, H.

"STABILITY OF A COUNTER-ROTATING VORTEX PAIR IMMERSSED IN CROSS-STREAM SHEAR FLOW"

AIAA Journal, Vol. 35, No. 2, February 1997, pp. 295-305

The three-dimensional stability and nonlinear evolution of a single vortex and a pair of vortices of opposite strength immersed in a weak cross-stream shear flow are examined. The shear flow rate is assumed to be sufficiently small compared to the average core vorticity that the vortex cross sections are nearly circular and the effect of stretching of the background shear flow is negligible, while being sufficiently large compared to the vortex mutual interaction frequency to significantly influence the stability of the vortex pair. The effect of shear flow on the long- and short-wave instabilities are studied using a combination of linear theory and numerical simulations for nonlinear disturbances. The presence of cross-stream shear is found to introduce a coupling between the symmetric and antisymmetric perturbation modes of the vortex pair, which leads to the development of three distinctly different types of long-wave vortex instabilities. One type of instability is dominated by the interaction of the vortex self-induced velocity with the shear flow. The second type of instability is dominated by interaction of the vortices with each other. In the third type of instability, both the shear flow and the mutual interaction of the vortices are important. The nonlinear evolution of the vortex

pair is qualitatively different for each of these three cases. For short-wave perturbations, the presence of cross-stream shear is found to increase the growth rate and wave-number range of the unstable perturbations, provided that the shearing rate is sufficiently large.

Marshall, J. S. and Chen, H.

"STABILITY OF A COUNTER-ROTATING VORTEX PAIR IMMERSSED IN CROSS-STREAM SHEAR FLOW"

AIAA Journal, Vol. 35, No. 2, February 1997, pp. 295-305

Three-dimensional stability and nonlinear evolution of a single vortex and a pair of vortices of opposite strength immersed in a weak cross-stream shear flow are examined. The shear flow rate S is assumed to be sufficiently small compared to the average core vorticity that the vortex cross sections are nearly circular and the effect of stretching of the background shear flow is negligible, while being sufficiently large compared to the vortex mutual interaction frequency to significantly influence the stability of the vortex pair. The effect of shear flow on the long- and short-wave instabilities are studied using a combination of linear theory and numerical simulations for nonlinear disturbances. The presence of cross-stream shear is found to introduce a coupling between the symmetric and antisymmetric perturbation modes of the vortex pair, which leads to the development of three distinctly different types of long-wave vortex instabilities. One type of instability is dominated by the interaction of the vortex self-induced velocity with the shear flow. The second type of instability is dominated by interaction of the vortices with each other. In the third type of instability, both the shear flow and the mutual interaction of the vortices are important. The nonlinear evolution of the vortex pair is qualitatively different for each of these three cases. For short-wave perturbations, the presence of cross-stream shear is found to increase the growth rate and wave-number range of the unstable perturbations, provided that the shearing rate is sufficiently large.

Marshall, J. S. and Gossler, A. A.

"SIMULATION OF SECONDARY VORTICITY EJECTION AND EVOLUTION DURING THREE-DIMENSIONAL VORTEX-CYLINDER INTERACTION"

2000 ASME Fluids Engineering Division Summer Meeting, June 2000

Results of direct numerical computations are reported for the problem of three-dimensional interaction between a circular cylinder and a vortex with axis oriented nominally orthogonal to the cylinder axis. The computations employ a new type of tetrahedral vorticity element (TVE) method which solves the vorticity transport and Biot-Savart equations using a tetrahedral mesh fit to a set of Lagrangian computational points. The computations examine the secondary vorticity field shed from the cylinder and its evolution in the presence of the primary vortex. Cases with background free-stream velocity oriented in different directions are considered. Computational results are found to be consistent with previous experimental flow visualization results.

Marshall, J. S. and Grant, J. R.

"A LAGRANGIAN VORTICITY COLLOCATION METHOD FOR VISCOUS, AXISYMMETRIC FLOWS WITH AND WITHOUT SWIRL"

Journal of Computational Physics, Vol. 138, 1997, pp. 302-33.

This paper presents a new Lagrangian vorticity collocation method for viscous, axisymmetric fluid flows with or without swirl. The velocity calculation is performed using a representation of the vorticity field in terms of Gaussian vortex rings for off-center points and Gaussian vortex blobs along the axis of symmetry. A matrix equation for the element 'amplitudes' is obtained via a collocation approach, by fitting the vorticity representation to the known vorticity values at the control points, prior to each velocity evaluation. This matrix equation is solved using an iterative procedure, which both speeds the calculation and filters out 'noise' in the element amplitudes. Viscous diffusion is accomplished with use of a diffusion velocity method, in which control points are moved with the sum of the local fluid velocity and an additional 'diffusion velocity' that accounts for the effect of viscosity on the spread of vorticity support. Derivatives are obtained by locally fitting a polynomial function to control points about a given control point via a least-square formulation and then differentiating the polynomial. This method is found to maintain high accuracy even for very irregularly spaced control points. The method introduced for viscous diffusion in the paper can also be used for three-dimensional vortex methods in general.

Marshall, J. S. and Grant, J. R.

"A METHOD FOR DETERMINING THE VELOCITY INDUCED BY HIGHLY ANISOTROPIC VORTICITY BLOBS"

Journal of Computational Physics, Vol. 126, 1996, pp. 286-298

Resolution of boundary layer flows at moderate or high Reynolds numbers with the vortex blob method requires a great many isotropic elements. In this paper, an approximate method for determination of the induced velocity from highly anisotropic vorticity blobs is presented, and issues related to use of anisotropic elements in calculations with vortex blob algorithms for high Reynolds number near-wall flows are examined. The method presented here can be used to determine the induced velocity from smooth blob functions of arbitrary form, provided that the vorticity length scale associated with the blob is much less in one direction than in orthogonal directions. The ratio of these length scales is called the blob aspect ratio, and is used as a small parameter to construct an asymptotic approximation to the induced velocity field. This method is applied in the present paper to derive induced velocity expressions for anisotropic Gaussian blob functions in both two and three dimensions. It is argued, using test calculations for a Blasius boundary layer, that although direct calculation of the induced velocity requires about an order of magnitude more CPU time for anisotropic Gaussian elements than for isotropic elements, this difference is more than made up for by a reduction of several orders of magnitude in the number of elements needed to resolve boundary layer flows at moderate to high Reynolds numbers. It is also found that the standard vortex blob representation leads to errors in the calculation of wall slip velocity and wall shear stress due to smoothing of the discontinuity between

the real and image vorticity fields at the wall, but that these errors can be avoided by placing doublet-type elements along the wall.

Marshall, J. S. and Grant, J. R.

"EVOLUTION AND BREAKUP OF VORTEX RINGS IN STRAINING AND SHEARING FLOWS"

Journal of Fluid Mechanics, Vol. 273, 1994, pp. 285-312.

A study of the effect of external straining and shearing flows on the evolution and form of breakup of vortex rings has been performed. Two orientations each of straining and shearing flows are considered. A theoretical analysis of the ring motion for small strain and shear rates is performed, and it is found that for shearing and straining flows in the plane of the ring, the ring may oscillate periodically. For a straining flow with compression normal to the initial plane of the ring, the linear theory predicts that the ring radius will expand with time. For shearing flow normal to the initial plane of the ring, the linear theory predicts tilting of the ring in the direction of the shear flow rotation. Numerical calculations are performed with both single vortex filaments and with a three-dimensional discrete vortex element method. The numerical calculations confirm the predictions of the linear theory for values of stress and strain rates below a certain critical value (which depends on the ratio of initial ring to core radii), whereas for strain and shear rates above this value the ring becomes very elongated with time and eventually pinches off. Three distinct regimes of long-time behavior of the ring have been identified. Regime selection depends on initial ring geometry and orientation and on values of strain and shear rates. These regimes include (i) periodic oscillations with no pinching off, (ii) pinching off at the ring center, and (iii) development of an elongated vortex pair at the ring center and wider 'heads' near the ends (with pinching off just behind the heads). The boundaries of these regimes and theoretical reasons for the vortex behavior in each case are described.

Marshall, J. S. and Grant, J. R.

"PENETRATION OF A BLADE INTO A VORTEX CORE: VORTICITY RESPONSE AND UNSTEADY BLADE FORCES"

Journal of Fluid Mechanics, Vol. 306, 1996, pp. 83-109.

Numerical calculations are performed for the problem of penetration into a vortex core of a blade travelling normal to the vortex axis, where the plane formed by the blade span and the direction of blade motion coincides with the normal plane of the vortex axis at the point of penetration. The calculations are based on a computational method, applicable for unsteady three-dimensional flow past immersed bodies, in which a collocation solution of the vorticity transport equation is obtained on a set of Lagrangian control points. Differences between this method and other Lagrangian vorticity-based methods in the literature are discussed. Lagrangian methods of this type are particularly attractive for problems of unsteady vortex-body interaction, since control points need only be placed on the surface of the body and in regions of the flow with non-negligible vorticity magnitude. The

computations for normal blade-vortex interaction (BVI) are performed for an inviscid fluid and focus on the relationship between the vortex core deformation due to penetration of the blade into the vortex ambient position and the resulting unsteady pressure field and unsteady force acting on the blade. Computations for cases with different vortex circulations are performed, and the accuracy of an approximate formulation using rapid distortion theory is assessed by comparison with the full computational results for unsteady blade force. The force generated from blade penetration into the vortex ambient position is found to be of a comparable magnitude to various other types of unsteady BVI forces, such as that due to cutting of the vortex axial flow.

Marshall, J. S. and Krishnamoorthy, S.

"ON THE INSTANTANEOUS CUTTING OF A COLUMNAR VORTEX WITH NON-ZERO AXIAL FLOW"

J. Fluid Mech., Vol. 351, 1977, pp. 41-74

A study of the response of a columnar vortex with non-zero axial flow to impulsive cutting has been performed. The flow evolution is computed based on the vorticity-velocity formulation of the axisymmetric Euler equation using a Lagrangian vorticity collocation method. The vortex response is compared to analytical predictions obtained using the plug-flow model of Lundgren & Ashurst (1989). The plug-flow model indicates that axial motion on a vortex core with variable core area behaves in a manner analogous to one-dimensional gas dynamics in a tube, with the vortex core area playing a role analogous to the gas density. The solution for impulsive cutting of a vortex obtained from the plug-flow model thus resembles the classic problem of impulsive motion of a piston in a tube, with formation of an upstream-propagating vortex 'shock' (over which the core radius changes discontinuously) and a downstream-propagating vortex 'expansion wave' on opposite sides of the cutting surface. Direct computations of the vortex response from the Euler equation reveal similar upstream- and downstream-propagating waves following impulsive cutting for cases where the initial vortex flow is subcritical. These waves in core radius are produced by a series of vortex rings, embedded within the columnar vortex core, having azimuthal vorticity of alternating sign. The effect of the compression and expansion waves is to bring the axial and radial velocity components to nearly zero behind the propagating vortex rings, in a region on both sides of the cutting surface with ever-increasing length. The change in vortex core radius and the variation in pressure along the cutting surface agree very well with the predictions of the plug-flow model for subcritical flow after the compression and expansion waves have propagated sufficiently far away.

Marshall, J. S. and Yalamanchill, R.

"VORTEX CUTTING BY A BLADE, PART II: COMPUTATIONS OF VORTEX RESPONSE"

AIAA Journal, Vol. 32, No. 7, July 1994, pp. 1428-1436.

Computations of the interaction between a line vortex and blades of various thicknesses and angles of attack traveling in a direction normal to the vortex axis have been performed. A procedure to enable instantaneous cutting of the vortex is used in the case of thin blades to study vortex interaction with

the blade both before and after vortex cutting has occurred. To isolate the effect of blade thickness on vortex bending, additional computations have been performed of the interaction between a line vortex and circular cylinders of various diameters. The vortex is represented by a filament model which includes axial flow within the core and nonuniform core area, and the effect of the blade or cylinder on the vortex is obtained using a vortex sheet panel method. The study particularly examines bending of the vortex and the subsequent variation in vortex core radius. It is found that the amount of vortex bending is primarily dependent on the blade thickness T (or diameter D of a circular cylinder) to ambient vortex core radius a . For blades with T/a of order unity or less, very little bending is observed for attack angles under the stall limit. For cases in which significant vortex bending is observed (T/a or D/a greater than order unity), increase in blade or cylinder forward speed results in a decrease in vortex core radius for a given amount of bending of the vortex axis. Vortex shocks and expansion waves are also observed to propagate on the vortex after cutting by a blade, as predicted in Part I of the study.

Marshall, J. S., Brancher, P. and Giovannini, A.

"INTERACTION OF UNEQUAL ANTI-PARALLEL VORTEX TUBES"

J. Fluid Mechanics, Vol. 446, 2001, pp. 229-252

A computational study is reported of the close interaction of nominally anti-parallel vortex tubes with unequal strengths, S_1 and S_2 , where S_2 is less than or equal to S_1 . The computations are performed using a spectral method, with periodic boundary conditions and vortex Reynolds number $Re = 1500$, and the vortices are perturbed by a wavelength for which the pair is unstable because of their mutual interaction. The numerical method is tested for the case of equal-strength vortices, which exhibits the classic vortex reconnection phenomenon typified by bridging between the vortex cores and formation of thin vorticity threads as the bridged sections advect away under their self-induced velocity. Computations for vortices of unequal strengths are reported for cases with small, moderate, and large strength differences, for which $S_2/S_1 = 0.82, 0.54$ and 0.25 are chosen as representative values. The bridges between the vortex structures form loops that twist owing to the unequal vortex strengths. In the thread region, the vortex interaction is controlled by competition between the effects of stretching of the weak vortex as it wraps around the stronger vortex and the core distortion induced on each vortex owing to the straining imposed by the opposing vortex. For cases with large vortex strength difference, the strong vortex remains nearly straight as the weak vortex wraps around it, inducing an interlaced pattern of positive and negative vorticity spirals within the core of the strong vortex. Over a long time, the bridge regions form loops that propagate away from the thread region for cases with small strength difference and wrap around the nearly columnar strong vortex for cases with large strength difference.

Marshall, J. S., Grant, J. R., Gossler, A. A. and Huyer, S. A.

"VORTICITY TRANSPORT ON A LAGRANGIAN TETRAHEDRAL MESH"

Journal of Computational Physics, Vol. 161, 2000, pp. 85-113

An integral vorticity method for computation of incompressible, three-dimensional, viscous fluid flows is introduced which is based on a tetrahedral mesh that is fit to Lagrangian computational points. A fast method for approximation of Biot-Savart type integrals over the tetrahedral elements is introduced, which uses an analytical expression for the nearest few elements, Gaussian quadratures for moderately distant elements, and a multipole expansion acceleration procedure for distant elements. Differentiation is performed using a moving least-squares procedure, which maintains between first- and second-order accuracy for irregularly spaced points. The moving least-squares method is used to approximate the stretching and diffusion terms in the vorticity transport equation at each Lagrangian computational point. A new algorithm for the vorticity boundary condition on the surface of an immersed rigid body is developed that accounts for the effect of boundary vorticity values both on the total vorticity contained within tetrahedra attached to boundary points and on vorticity diffusion from the surface during the time step. Sample computations are presented for uniform flow past a sphere at Reynolds number 100, as well as computations for validation of specific algorithms.

Marshall, M. S. and Beninati, M. L.

"EXTERNAL TURBULENCE INTERACTION WITH A COLUMNAR VORTEX"

J. Fluid Mech., Vol. 540, 2005, pp. 221-245

A study was performed using direct numerical simulation to examine the interaction of external turbulence with a nominally columnar, large-scale vortex at a vortex Reynolds number of 3000. A multi-step procedure is used to generate initial conditions in which the external turbulence has the wrapped, neatly azimuthal form characteristic of turbulence around a large-scale vortex structure. The proper-orthogonal decomposition method is used to extract specific modes of the vortex turbulence that dominate the kinetic energy and enstrophy fields. The effect of turbulence initial intensity and length scale on the turbulence structure and its influence on the large-scale vortex are examined. It is observed that the external turbulence wraps around the large-scale vortex and advects radially inward toward the vortex core. The dominant axial length scale of the external turbulence appears to scale with the vortex core diameter, with the mode with the largest enstrophy having a wavelength of about twice the core diameter. The turbulence induces a bending wave on the vortex core with axial wavelength approximately equal to the dominant wavelength of the external turbulence. The turbulent enstrophy decays according to a power-law expression for cases with moderate initial turbulence intensity. For sufficiently strong initial turbulence intensity, the turbulence breaks up the large-scale vortex core, creating strong turbulence within the vortex core.

Marshall, R. E. and Mudukutore, A. S.

"WAKE VORTEX RADAR SIMULATION STUDIES"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 309-323

Wake vortex radar reflectivity models in clear air and fog; and 35 GHz Wake Vortex pulse compression radar simulations in fog are presented.

Marshall, R. E. and Mudukutore, A. S.

"SPATIO-TEMPORAL CHARACTERISTICS OF RADAR VOLUME REFLECTIVITY IN WINGTIP GENERATED WAKE VORTICES IN CLEAR AIR"

Twenty-eighth Conference on Radar Meteorology, Austin, TX, September 7-12, 1997, Preprints, American Meteorological Society, 1997, pp. 266-267

The NASA Terminal Area Simulation System (TASS) has been modified to predict the mean wind and thermodynamic variables for aircraft 2D wakes with a 1-m resolution. The TASS-derived turbulent kinetic energy dissipation rate and kinematic viscosity have been used to calculate the Kolmogorov microscale and a corresponding maximum radar frequency at each grid point within aircraft wakes.

Marshall, R. E. and Mudukutore, A. S.

"RADAR REFLECTIVITY FACTOR IN THE WAKES OF AIRCRAFT IN FOGS"

Proceedings 28th Conf. on Radar Meteorology, American Meteorology Society, Austin, TX, September 1997, pp. 159-160

Doppler radar has been suggested as a remote sensor for aircraft wake vortex quantification in adverse weather, with a view to the dynamic adjustment of wake vortex separation distances between aircraft at takeoffs and landings. Results are presented from predictions of the radar reflectivity factor in the wakes of aircraft flying in fogs.

Marshall, R. E. and Myers, T.

"WINGTIP GENERATED WAKE VORTICES AS RADAR TARGETS"

IEEE Aerospace and Electronic Systems Magazine, Vol. 11, No. 12, December 1996, pp. 27-30

Previous radar wake vortex detection experiments have resulted in measured beam averaged values of radar reflectivity from wake vortices in clear air. We have employed average wind and thermodynamic variable output from a two-dimensional wake vortex model in clear air and fog to predict radar reflectivity in a wake vortex on a one-meter grid. The results agree well, compared to data in the literature. In the clear air case, scales of turbulence were analyzed at each grid point to determine the appropriate maximum radar frequency for detection. Initial wake structure, transport, and vortex persistence are related to atmospheric winds, atmospheric stability, and generating aircraft characteristics.

Marshall, R. E., Montoya, J., Richards, M. A. and Galliano, J.

"CHARACTERISTICS OF CIVIL AVIATION ATMOSPHERIC HAZARDS"

Fifth and Final Combined Manufacturers' and Technologists' Conference, Part 2, Airborne Windshear Detection and Warning Systems, NASA Langley Research Center, VA, July 1994, pp. 545-568

Clear air turbulence, wake vortices, dry hail, and volcanic ash are hazards to civil aviation that have not been brought to the forefront of public attention by a catastrophic accident. However, these four hazards are responsible for major and minor injuries, emotional trauma, significant aircraft damage, and in route and terminal area inefficiency. Most injuries occur during clear air turbulence. There is significant aircraft damage for any volcanic ash encounter. Rolls induced by wake vortices occur near the ground. Dry hail often appears as an area of weak echo on the weather radar. This paper will present the meteorological, electromagnetic, and spatiotemporal characteristics of each hazard. A description of a typical aircraft encounter with each hazard will be given. Analyzed microwave and millimeter wave sensor systems to detect each hazard will be presented.

Marshall, R. E., Mudukutore, A. S. and Wissel, V. L. H.

"RADAR REFLECTIVITY IN WINGTIP-GENERATED WAKE VORTICES"

NASA/CR-97-206259, December 1997, Center for Aerospace Technology, Research Triangle Institute, Hampton, VA

This report documents new predictive models of radar reflectivity, with meter-scale resolution, for aircraft wakes in clear air and fog. The models result from a radar design program to locate and quantify wake vortices from commercial aircraft in support of the NASA Aircraft Vortex Spacing System. The radar reflectivity model for clear air assumes: 1) turbulent eddies in the wake produce small discontinuities in radar refractive index; and 2) these turbulent eddies are in the 'inertial subrange' of turbulence. From these assumptions, the maximum radar frequency for detecting a particular aircraft wake, as well as the refractive index structure constant and radar volume reflectivity in the wake can be obtained from the NASA Terminal Area Simulation System (TASS) output. For fog conditions, an empirical relationship is used to calculate radar reflectivity factor from TASS output of bulk liquid water. Currently, two models exist: 1) Atlas -- based on observations of liquid water and radar reflectivity factor in clouds; and 2) de Wolf -- specifically tailored to a specific measured dataset (1992 Vandenberg Air Force Base).

Marshall, R. E., Mudukutore, A. S., Wissel, V. L. H. and Myers, T.

"THREE-CENTIMETER DOPPLER RADAR OBSERVATIONS OF WINGTIP-GENERATED WAKE VORTICES IN CLEAR AIR"

NASA/CR-97-206260, December 1997, Center for Aerospace Technology, Research Triangle Institute, Hampton, VA

This report documents a high risk, high pay-off experiment with the objective of detecting, for the first time, the presence of aircraft wake vortices in clear air using X-band Doppler radar. Field experiments were conducted in January 1995 at the Wallops Flight Facility to demonstrate the capability of the 9.33 GHz (3 cm) radar, which was assembled using an existing nine-meter parabolic antenna reflector and the receiver/transmitter from the NASA Airborne Windshear Radar Program. A C-130 aircraft, equipped with wingtip smoke generators, created visually marked wake vortices, which were recorded by video cameras. A C-band radar also observed the wake vortices during detection attempts with the X-band radar. Rawinsonde data was used to calculate vertical soundings of wake vortex decay time, cross aircraft bearing wind speed, and water vapor mixing ratio for aircraft passes over the radar measurement range. This experiment was a pathfinder in predicting, in real time, the location and persistence of C-130 vortices, and in setting the flight path of the aircraft to optimize X-band radar measurement of the wake vortex core in real time.

Marshall, J. S. and Grant, J. R.

"COMPUTATION AND MODELING OF BLADE PENETRATION INTO A VORTEX IN AN INVISCID FLUID"

AIAA Paper 1995-2239, June 1995, San Diego, CA.

The penetration of a blade into the core region of a three-dimensional vortex structure, where the blade centerplane is normal to the vortex axis, is studied numerically. The computations are performed using a new type of Lagrangian vortex method, in which the amplitudes of the vortex blobs are obtained by iterative solution of an inverse problem. The algorithm used for solution of blade surface pressure is also new and is based on a boundary-integral formation of the pressure-Poisson equation. The variation with time of the force on the blade is obtained for vortices of a variety of strengths. The computed results are found to compare to those which would be obtained under the rapid distortion approximation, but to differ significantly from results obtained under the 'frozen vortex' assumption.

Martin, A.

"AN ACOUSTIC TOMOGRAPHY SYSTEM FOR MAKING HIGH RESOLUTION MEASUREMENTS OF AIRCRAFT WAKE VORTICES"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

An acoustic tomography system has been successfully deployed at Melbourne Airport. The system uses acoustic chirp pulses over the range 1000 Hz to 2000 Hz of 0.5 sec in length and has a matched filter receiver. Preliminary measurements show that high spatial and temporal measurements of aircraft wake vortices can be made on landing and departing aircraft. The system provides spatial resolution of around 2 m, temporal resolution of 2.7 sec with exceptional signal-to-noise ratio providing the opportunity for all weather operation. The measurement window is 110 m on both sides of the runway centerline up to a height of 100 m. A very high-resolution wind profiler that uses the same acoustic technology as the wake vortex detector will be collocated and provide essential information

about the local structure of the atmosphere, information that should be useful to assist with the completion of the development of wake evolution models and theory.

Martin, A. L.

"MEASUREMENT OF AIR CHARACTERISTICS IN THE LOWER ATMOSPHERE"

US Patent 7,317,659 B2, January 2008.

Sodar systems and methods for acoustically sounding air are disclosed in which chirps longer than 300 ms -- and preferably with durations of tens of seconds -- are used along with matched filter and/or Fourier processing methods to derive phase signals indicative of air characteristics in range. A listen-while-transmit strategy is preferred, the direct signal being removed by subtracting the phase signals from two or more receivers located near the transmitter so as to be in the same noise environment. The resultant differential signals can be related to cross-range wind with range distance. In one example, apparatus is employed comprising a reflector dish over which one central loudspeaker and four microphones are mounted, the microphones preferably being located on cardinal compass points and having their axes slightly angled with respect to the vertical transmission axis.

Martin, A. L.

"DETECTION OF WAKE VORTICES AND THE LIKE IN THE LOWER ATMOSPHERE"

U.S. Patent 2007/0089502 A1, April 2007

Two SODAR systems for detecting and characterizing vortices shed from landing or departing aircraft as at an airport are positioned so that one, the active system is located beneath the likely vortices and the other, the reference system is located away from the vortices but in the same ambient environment. Thus, where a wind duct or thermal inversion is present, both SODAR systems will detect echoes and generated thereby, whereas only the active system will detect echoes from wake vortices. By differencing the outputs of the reference and active systems, better vortex identification and discrimination is achieved. Only one SODAR system need be used where sufficiently normal conditions prevail between aircraft activity, since readings taken in the absence of aircraft can be used as reference data for subtraction from 'active' data recorded during the presence of aircraft.

Martin, F. W. and Walkley, K. B.

"IMAGE SYSTEM SOLUTION FOR STORE AERODYNAMICS WITH INTERFERENCE - PART II"

J. Aircraft, Vol. 12, No. 3, 1975, pp. 156-161

The mutual aerodynamic interference problem for external aircraft-stores has been analyzed using the image system technique. To facilitate this analysis, it has been assumed that small perturbation solutions are valid. It is further assumed that the external stores are slender, axisymmetric bodies and that the mutual interference can be analyzed by first assuming a cross-flow solution. Both body-body

and wing-body interference solutions have been obtained. The first were considered in Part I of this paper. For the wing-body solution, the image systems in the cross-flow plane consist of vortex pairs appropriately located by using the Milne-Thomson circle theorem. The strengths of the image vortex system are then determined by satisfying the body boundary conditions at designated control points on the external stores. Good agreement has been found between the theoretical and experimental results.

Martin, P. B.

"MEASUREMENTS OF THE TRAILING VORTEX FORMATION, STRUCTURE AND EVOLUTION IN THE WAKE OF A HOVERING ROTOR"

PhD Thesis, 2001, University of Maryland, College Park, Maryland.

High-resolution velocity field measurements and flow visualization images were acquired in the flow field near the tip of a rotor blade operating in hover. Using three-dimensional laser Doppler velocimetry (LDV), the measurements documented the trailing vortex formation, initial structure, and the viscous evolution of the core. The test conditions covered a range of wake ages from as young as one degree, up to about one rotor revolution. For each wake age, vortex core properties were estimated from the velocity field measurements. The test conditions also included different tip shapes including rectangular, tapered, swept, and a sub wing tip. Preliminary measurements were used to refine the technique by understanding the sources of uncertainty and the spatial resolution requirements. This task included developing a new procedure for three-component LDV alignment using a laser beam profiler. A detailed uncertainty analysis of the LDV measurement technique was conducted and applied to helicopter rotor blade tip vortex measurements. Finally, spatial resolution requirements were formally established to enable a more accurate reconstruction of the velocity field associated with blade tip vortices. A set of benchmark test cases was acquired using LDV for each of the tip shapes. The measurements were supported by detailed flow visualization. The high spatial resolution obtained with LDV has shown that the tip vortex core radius can be less than 3 percent chord at early wake-ages, but grows asymptotically as it ages. A significant axial velocity deficit existed in the vortex core that was of the order of the peak swirl velocity at early wake-ages, but which quickly diminished as the vortex aged. The evidence suggests that the entire tip vortex structure is neither fully laminar or fully turbulent, but is instead in a continuous state of dynamic evolution with a region of relatively slow laminar diffusion and a region of accelerated turbulent diffusion.

Martin, P. B. and Leishman, J. G.

"TRAILING VORTEX MEASUREMENTS IN THE WAKE OF A HOVERING ROTOR BLADE WITH VARIOUS TIP SHAPES"

58th Annual Forum and Technology Display of the American Helicopter Society International, Montreal, Canada, June 2002

This work examined the wake aerodynamics of a single helicopter rotor blade with several tip shapes operating on a hover test stand. Velocity field measurements were conducted using three-component laser Doppler velocimetry (LDV). The objective of these measurements was to document the vortex velocity profiles and then extract the core properties, such as the core radius, peak swirl velocity, and axial velocity. The measured test cases covered a wide range of wake-ages and several tip shapes, including rectangular, tapered, swept, and a sub wing tip. One of the primary differences shown by the change in tip shape was the wake geometry. The effect of blade taper reduced the initial peak swirl velocity by a significant fraction. It appears that this is accomplished by decreasing the vortex strength for a given blade loading. The sub wing measurements showed that the interaction and merging of the sub wing and primary vortices created a less coherent vortical structure. A source of vortex core instability is shown to be the ratio of the peak swirl velocity to the axial velocity deficit. The results show that if there is a turbulence producing region of the vortex structure, it will be outside of the core boundary. The LDV measurements were supported by laser light-sheet flow visualization. The results provide several benchmark test cases for future validation of theoretical vortex models, numerical free-wake models, and computational fluid dynamics results.

Martin, P. B., Leishman, J. G., Pugliese, G. J. and Anderson, S.L.

"STEREOSCOPIC PIV MEASUREMENTS IN THE WAKE OF A HOVERING ROTOR"

56th Annual Forum of the American Helicopter Society, Virginia Beach, VA, May 2000

Phase-resolved stereoscopic particle image velocimetry (PIV) measurements were made in the wake of a hovering sub-scale helicopter rotor. The results were compared with three-component laser Doppler velocimetry (LDV) measurements when using the same seeding medium. The various challenges of using PIV and LDV to study the formation and evolution of helicopter tip vortices are discussed. Results are presented for a test case using a hovering rotor with a tapered tip blade. The relatively small tip vortex core size and high tangential velocities produced by the blade provided a particularly good challenge to the spatial resolution of the PIV technique. The large image area covered by the PIV measurements provided insight into the rotor flow physics. Compared to LDV, however, it was found that PIV was generally unable to resolve the steep velocity gradients present in the tip vortex. While PIV provides certain advantages when used as a complimentary technique to LDV, the results show that it is not yet a substitute when three-dimensional vortex velocity profile measurements with high spatial and temporal resolution are required.

Martina, A. P.

"METHOD FOR CALCULATING THE ROLLING AND YAWING MOMENTS DUE TO ROLLING FOR UNSWEPT WINGS WITH OR WITHOUT FLAPS OR AILERONS BY USE OF NONLINEAR SECTION LIFT DATA"

NASA TN 1167, January 1954, Langley Aeronautical Laboratory, Langley Field, VA.

The methods of NACA Reports 865 and 1090 have been applied to the calculation of the rolling-moment and yawing-moment coefficients due to rolling for unswept wings with or without flaps or

ailerons. The methods are based on lifting-line theory and allow the use of nonlinear section lift data. The method presented herein permits calculations to be made somewhat beyond maximum lift for wings having no twist or continuous twist and employing airfoil sections which do not display large discontinuities in the lift curves. Calculations can be made up to a maximum lift for wings with discontinuous twist such as that produced by partial-span flaps or ailerons, or both. Two calculated examples are presented in simplified computing forms in order to illustrate the procedures involved.

Martinez-Val, R.

"FLYING WINGS, A NEW PARADIGM FOR CIVIL AVIATION"

Acta Polytechnica, Vol. 47, No. 1, 2007, pp. 32-43.

Over the last 50 years, commercial aviation has been mainly based what is currently called the conventional layout, characterized by a slender fuselage mated to a high aspect ratio wing, with aft-tail planes and pod-mounted engines under the wing. However, it seems that this primary configuration is approaching an asymptote in its productivity and performance characteristics. One of the most promising configurations for the future is the flying wing in its distinct arrangements: blended-wing-body, C-wing, tail-less aircraft, etc. These layouts might provide significant fuel savings and, hence, a decrease in pollution. The present paper discusses the main features of flying wings, their advantages over conventional competitors, and some key operational issues, such as evacuation and vortex wake intensity.

Maskew, B.

"SUBVORTEX TECHNIQUE FOR THE CLOSE APPROACH TO A DISCRETIZED VORTEX SHEET"

J. Aircraft, Vol. 14, No. 2, 1977, pp. 188-193.

The close-approach problem associated with flow calculation methods based on vortex-lattice theory is examined numerically using two-dimensional discretized vortex sheets. The analysis first yields a near-field radius of approximately the distance apart of the vortices in the lattice; only within this distance from the sheet are the errors arising from the discretization significant. Various modifications to the discrete vortices are then considered with the objective of reducing the errors. This study leads to a near-field model in which a vortex splits into an increasing number of sub vortices as it is approached. The sub vortices, whose strengths vary linearly from the vortex position, are evenly distributed along an interpolated curve passing through the basic vortices. This sub vortex technique can be extended to the three-dimensional case and is efficient because the number of vortices is effectively increased, but only where and when needed.

Maskew, B.

"ON THE INFLUENCE OF CAMBER AND NON-PLANAR VORTEX WAKE ON WING CHARACTERISTICS IN GROUND EFFECT"

ARC CP-1264, 1973, Loughborough Univ. of Technology, Loughborough, England

The theoretical influence of camber and non-planar wake on the change of lift, vortex drag and center of pressure of a wing with ground effect is examined. Potential flow calculations are performed for both two- and three-dimensional conditions, the former using a multi-vortex method and the latter using an arbitrary geometry quadrilateral vortex-ring method with a vortex wake relaxation iterative scheme. The results demonstrate the importance of including the influence of camber, incidence, and non-planar wake in practical ground effect calculations.

Maslowe, S. A. and Nigam, N.

"THE NONLINEAR CRITICAL LAYER FOR KELVIN MODES ON A VORTEX WITH A CONTINUOUS VELOCITY PROFILE"

SIAM Journal on Applied Mathematics, Vol. 68, Issue 3, 2008, pp. 825-843.

We consider in this paper the propagation of neutral modes along a vortex with velocity profile $V(r)$, r being the radial coordinate. In the linear inviscid stability theory for swirling flows, modes that are singular at some value of r denoted r_c , the critical point, are particularly significant. The singularity can be dealt with by adding viscous and/or nonlinear effects within a thin critical layer centered on the critical point. At high Reynolds numbers, the case of most interest in applications such as aeronautics and geophysical fluid dynamics, nonlinearity is the appropriate choice, although viscosity may still play a subtle role. We determine here the scaling and equations that govern the nonlinear critical layer. The method of characteristics is then employed to obtain an exact solution of the governing inviscid system composed of four coupled PDE's, of which two are nonlinear and two are linear. Finally, assuming zero phase change across the critical layer, solutions are obtained for the outer eigenvalue problem demonstrating the existence of modes not possible in a linear theory. This result may have important implications for the short wake cooperative instability mechanism that has received so much attention in the context of aircraft trailing vortices.

Mason, J. O., Aguirre, R. C. and Catrakis, H. J.

"COMPUTATIONAL AERO-OPTICS AND ELECTROMAGNETICS: COMPRESSIBLE VORTICES AND LASER BEAM PROPAGATION"

IASME Transactions, Issue 1, Vol. 2, January 2005, pp. 19-27

Computational modeling of electromagnetic-wave propagation, such as laser-beam propagation, through turbulent flows involves, as basic elements, the interactions between each vortex and each optical wavefront. We consider a compressible vortex as a flow model relevant to the large-scale as well as small-scale structure of turbulence. The compressibility is essential for applications associated with airborne platforms such as mobile laser communication or directed-energy projection. A weakly-compressible two-dimensional axisymmetric steady isentropic vortex model is employed. The full

nonlinear eikonal equation is numerically integrated to propagate the optical wavefronts through the vortex. For near-field aero-optics applications at low beam energies, geometrical optics is sufficient. The optical-path-length profile of the propagated distorted wavefronts is computed, confirming the acceleration of the beam wavefronts through the density low of the vortex. The optical distortion is found to be weakly sensitive to an approximation of the aero-optical interaction where bending of individual light rays is neglected. This provides a computationally-efficient means of simulating aero-optical distortions through low-compressibility vortices in the near-field of the laser beam.

Mason, W. H. and Marchman iii, J. F.

"THE FARFIELD STRUCTURE OF AIRCRAFT WAKE TURBULENCE"

AIAA Paper No. 72-40, Jan. 1972, San Diego, CA.

Detailed mean flow measurements were obtained at stations up to thirty chord lengths downstream in an airfoil trailing vortex using a yawhead pressure probe in the Virginia Tech Six-Foot Subsonic Tunnel. Mass injection at the wingtip was shown to hasten the vortex decay. A theoretical method has been developed to show the effect of wing circulation distribution on the structure of the outer portion of the vortex and excellent agreement with the experimental data is demonstrated. Experimental results indicate a much slower decay and higher tangential velocities than previously expected.

Mason, W. H. and Marchman, III, J. F.

"FAR-FIELD STRUCTURE OF AIRCRAFT WAKE TURBULENCE"

J. Aircraft, Vol. 10, No. 2, February 1973, pp. 86-92

Detailed mean flow measurements were obtained at stations up to thirty chord lengths downstream in an airfoil trailing vortex using a yawhead pressure probe in the Virginia Tech Six-Foot Subsonic Tunnel. Mass injection at the wingtip was shown to hasten the vortex decay. A theoretical method has been developed to show the effect of wing circulation distribution on the structure of the outer portion of the vortex and excellent agreement with the experimental data is demonstrated.

Mason, W. H. and Marchman, III, J. F.

"FARFIELD STRUCTURE OF AN AIRCRAFT TRAILING VORTEX, INCLUDING EFFECTS OF MASS INJECTION"

NASA CR-62078, April 1972, Virginia Polytechnic Inst. and State Univ., Blacksburg, VA.

With the introduction of the 'Jumbo Jet' class of aircraft it has become important to predict the aircraft wake turbulence due to the tip trailing vortex accurately. A yawhead pressure probe has been used in the Virginia Tech 6-Foot Subsonic Tunnel to obtain detailed mean flow measurements at stations up to thirty chord lengths downstream in an aircraft trailing vortex. Mass injection at the wingtip has been shown to hasten the decay of the trailing vortex. A theoretical method has been given to show the effect of the circulation distribution on the wing on the structure of the outer portion

of the vortex, and excellent agreement with experiment has been shown. Experimental results indicate a much slower decay and higher tangential velocities than previously expected.

Mason, W. H. and Marchman, III, J. F.

"INVESTIGATION OF AN AIRCRAFT TRAILING VORTEX USING A TUFT GRID"

VPI-E-71-17, September 1971, Virginia Polytechnic Institute and State University, Blacksburg, VA

A study of the trailing vortex of a wing has been made using a tuft grid in the Virginia Tech 6 Foot Wind Tunnel. The study included an investigation of the use of mass injection at the wing tip as a means of destroying the vortex. Test results show that a fully developed, stable, vortex exists at least a distance of thirty chord lengths downstream of the wing, and that the 'swirl' of the vortex can be reduced or eliminated by mass injection at the wing tip.

Massimini, S. V.

"SIMULTANEOUS INDEPENDENT AND DEPENDENT PARALLEL INSTRUMENT APPROACHES;
ASSUMPTIONS, ANALYSIS, AND RATIONALE"

MP 06W0000127, July 2006, MITRE Corporation, McLean, VA.

The Federal Aviation Administration has successfully conducted simultaneous independent approaches to parallel runways for over 40 years using Instrument Landing System (ILS) navigation and terminal radar monitoring. Parallel dependent approaches have also been conducted for many years. Recent advances in navigation and surveillance have sparked interest in reviewing the current standards for these approaches. This paper will attempt to describe the process that led to the current standards, including relevant assumptions, testing, and methodology. Future work will identify the most promising assumptions for further review.

Massouh, F. and Dobrev, I.

"INVESTIGATION OF WIND TURBINE FLOW AND WAKE"

Journal of Fluid Science and Technology, Vol. 9, No. 3, 2014, pp. 1-9.

This paper is dedicated to the investigation and analysis of wind turbine wake. An experimental work is undertaken in wind tunnel on a horizontal axis wind turbine model. The velocity field in the wake is measured using PIV with phase synchronization to relate velocity and vortices to the rotating blades. The tip vortices are investigated in successive azimuthal positions of the rotor. A specially developed algorithm based on the circulation maximum detects the positions of the vortex cores and permits to use conditional averaging technique. The analysis of obtained velocity fields enables to determine the vortex core diameter, the swirl velocity distribution, and the vortex diffusion as functions of the vortex age. The quality of obtained results permits to use them as reference for the validation of numerical computations.

Mast, E. H. M., Vermeer, L. J. and van Bussel, G. J. W.

"ESTIMATION OF THE CIRCULATION DISTRIBUTION ON A ROTOR BLADE FROM DETAILED NEAR WAKE VELOCITIES"

Wind Energy, Vol. 7, 2004, pp. 189-209

The circulation distribution over a blade of a wind turbine model is estimated by use of a vortex model, which is matched with measured wake properties. With near wake velocities and the Biot-Savart law an optimization scheme is constructed to estimate the circulation distribution over the blade using a polynomial function series to approximate the circulation distribution. The velocities resulting from the calculated distribution are compared with the measured data, and deviations are discussed and explained. The vortex model offers insight into how the measured velocities can be separated into induced velocities of the different parts of the vortex system, such as the influence of the tip vortex. Finally, the circulation distribution obtained with the vortex model is compared with the circulation distribution obtained through application of a blade element momentum (BEM) code. The BEM results show an underestimation of the circulation near the root and an overestimation of the circulation near the tip with respect to the vortex model results.

Matalanis, C. G.

"WAKE VORTEX ALLEVIATION USING RAPIDLY ACTUATED SEGMENTED GURNEY FLAPS"

PhD Thesis, January 2007, Stanford University, Stanford, CA.

All bodies that generate lift also generate circulation. The circulation generated by large commercial aircraft remains in their wake in the form of trailing vortices. These vortices can be hazardous to following aircraft due to their strength and persistence. To account for this, airports abide by spacing rules which govern the frequency with which aircraft can take-off and land from their runways when operating in instrument flight rules. These spacing rules have become the limiting factor on increasing airport capacity, and with the increases in air travel predicted for the near future, the problem is becoming more urgent. One way of approaching this problem is active wake alleviation. The basic idea is to actively embed perturbations in the trailing vortex system of an aircraft which will excite natural instabilities in the wake. The instabilities should result in a wake which is benign to following aircraft in less time than would normally be required, allowing for a reduction in current spacing rules. The main difficulty with such an approach is in achieving perturbations large enough to excite instability without significantly degrading aircraft performance. Rapidly actuated segmented Gurney flaps, also known as Miniature Trailing Edge Effectors (MiTEs), have shown great potential in solving various aerodynamic problems. Previous work has shown that they can create a large increment in the section lift coefficient of an airfoil local to the spanwise position where they are actuated. Thus, MiTEs may be used to actively alter the shape of a wing lift distribution. This suggests that they might also be useful for active wake alleviation. We conducted an experimental and computational study to assess the potential for using MiTEs for active wake vortex alleviation. Wind tunnel tests were performed on a half-span model NACA 0012 wing equipped with an array of 13 independent MiTE pairs. The chord-based Reynolds

number was around 350,000. Each MiTE could extend 0.015 chord lengths perpendicular to the freestream on the pressure side of the wing. Pressure profiles and a five-hole probe survey in the near wake were used to examine the influence that the MiTEs had upon the wing aerodynamics and the vortex rollup process. Static and dynamic particle image velocimetry (PIV) were used to measure the static and time-dependent response of the vortex in the intermediate wake to various MiTE actuation schemes. These experiments showed that the MiTEs could deflect the vortex in both the spanwise and lift directions. A maximum spanwise deflection of 0.041 chord lengths was possible while nearly conserving lift. The dynamic PIV results combined with results from the pressure profiles and a five-hole probe survey in the intermediate wake were used to form complete, experimentally-based initial conditions for vortex filament computations that were used to compute the far wake evolution. Results from these computations showed that the perturbations created by MiTEs could be used to excite a variety of three-dimensional inviscid vortex instabilities. Finally, the research performed on MiTEs led to the development of a new, more practical wake alleviation device: the spanwise actuating Gurney flap. A prototype of this device was designed and tested. The tests showed that the same types of perturbations as were seen with the MiTEs could be achieved with this device.

Matalanis, C. G. and Eaton, J. K.

"WAKE VORTEX CONTROL USING RAPIDLY ACTUATED SEGMENTED GURNEY FLAPS"

AIAA Paper No. 2006-481, Reno, NV, January 2006

A study to assess the potential for using rapidly actuated segmented Gurney flaps, also known as Miniature Trailing Edge Effectors (MiTEs), for active wake vortex alleviation is conducted using a half-span model wing with NACA 0012 shape and an aspect ratio of 4.1. All tests are performed with the wing at an 8.9-degree angle of attack and chord based Reynolds number of 350,000. The wing is equipped with an array of 13 MiTE pairs. Each MiTE has a flap that in the neutral position rests behind the blunt trailing edge of the wing, and in the down position extends 0.015 chord lengths perpendicular to the freestream on the pressure side of the wing. Measurements of section lift coefficient are made using pressure taps to assess the effect of various MiTE configurations on the spanwise lift distribution. Static and dynamic PIV measurements are made on the trailing vortex to assess the steady-state and transient effects of different actuation schemes. It is found that the MiTE configurations that nearly conserve the total lift on the wing can also displace the vortex by 0.041 chord lengths in the spanwise direction and 0.016 chord lengths in the liftwise direction. These perturbations can be produced at axial wavelengths corresponding to short and long wavelength vortex instabilities.

Matalanis, C. G. and Eaton, J. K.

"WAKE VORTEX ALLEVIATION USING RAPIDLY ACTUATED SEGMENTED GURNEY FLAPS"

AIAA Journal, Vol. 45, No. 8, August 2007, pp. 1874-1884

A study to assess the potential for using rapidly actuated segmented Gurney flaps, also known as miniature trailing-edge effectors, for active wake vortex alleviation is conducted. Experiments are

performed using a half-span model wing with NACA 0012 shape and an aspect ratio of 4.1. The wing is at an 8.9-deg angle of attack and the chord-based Reynolds number is around 350,000. It is equipped with an array of miniature trailing-edge effectors that extend 0.015 chord lengths perpendicular to the freestream on the pressure side of the wing when deployed and sit just behind the blunt trailing edge when retracted. Measurements of section lift coefficient and the velocity field in the intermediate wake using dynamic particle image velocimetry and a five-hole probe delineate the time-varying perturbation imparted by the miniature trailing-edge effectors upon the trailing vortex while keeping the lift nearly constant. The data are used to form a complete initial condition for a vortex filament computation of the far-wake evolution. Cases at the model-scale and full-scale configurations are computed. The results show that actuator-induced perturbations can be used to excite a variety of inviscid vortex instabilities.

Matalanis, C. G. and Eaton, J. K.

"WAKE VORTEX CONTROL USING STATIC SEGMENTED GURNEY FLAPS"

AIAA Journal, Vol. 45, No. 2, February 2007, pp. 321-328

A study to assess the potential for using static segmented Gurney flaps, also known as miniature trailing edge effectors, for active wake vortex alleviation is conducted using a half-span model wing with NACA 0012 shape and an aspect ratio of 4.1. All tests are performed with the wing at an 8.9 deg angle of attack and chord-based Reynolds number around 350,000. The wing is equipped with an array of 13 miniature trailing edge effector pairs. Each miniature trailing edge effector has a flap that in the neutral position rests behind the blunt trailing edge of the wing, and in the down position extends 0.015 chord lengths perpendicular to the freestream on the pressure side of the wing. Measurements of section lift coefficient are made using pressure taps to assess the effect of various miniature trailing edge effector configurations on the spanwise lift distribution. Particle image velocimetry and five-hole probe measurements are made on the trailing vortex to assess the steady-state effects of different flap configurations. It is found that the miniature trailing edge effector configurations with a large fraction of the span actuated down can deflect the vortex predominantly in the lift direction, whereas miniature trailing edge effector configurations with a small fraction of the span actuated down are able to deflect the vortex in both the spanwise and lift direction. A maximum spanwise deflection of 0.041 chord lengths is possible while nearly conserving total lift. These results suggest that certain miniature trailing edge effector configurations, if varied in time, may be useful for wake alleviation.

Matalanis, C. G. and Eaton, J. K.

"WAKE VORTEX ALLEVIATION USING RAPIDLY ACTUATED SEGMENTED GURNEY FLAPS"

Report No. 102 , Dept. Mechanical Engineering, Stanford, Univ., Stanford, CA, January 2007

The basic idea is to actively embed perturbations in the trailing vortex system of an aircraft which will excite natural instabilities in the wake. The instabilities should result in a wake which is benign to following aircraft in less time than would normally be required, allowing for reduction in current

spacing rules. The main difficulty with such an approach is in achieving perturbations large enough to excite instability without significantly degrading aircraft performance. Rapidly actuated segmented Gurney flaps, also known as Miniature Trailing Edge Effectors (MiTEs), have shown great potential in solving various aerodynamic problems. Previous work has shown that they can create a large increment in the section lift coefficient of an airfoil local to the spanwise position where they are actuated. Thus, MiTEs may be used to actively alter the shape of a wing lift distribution. This suggests that they might also be useful for active wake alleviation.

Matalanis, C. G., Nelson, G. D. and Eaton, J. K.

"NOVEL AERODYNAMIC DEVICE FOR WAKE VORTEX ALLEVIATION"

AIAA Journal, Vol. 45, No. 9, September 2007, pp. 2348-2350

Previous work conducted on rapidly actuated segmented Gurney flaps for wing tip vortex control has led to the development of a novel aerodynamic device specifically designed for active wake alleviation. The spanwise actuating Gurney flap constitutes a simple, practical, and implementable device capable of perturbing a trailing vortex in a manner that may excite wake instability. Although dynamic effects were not examined here, results from other Gurney flap-type devices suggest that at the slow actuation speeds that would be necessary to excite long wavelength instabilities, the response will likely be quasi steady. More work will be required to determine the optimal shape and configuration for such a device as well as the best way to implement it on a multi-element high lift wing.

Matayoshi, N.

"DYNAMIC WAKE VORTEX SEPARATION COMBINING WITH TRAFFIC OPTIMIZATION"

ICAS 2014, September 2014, St. Petersburg, Russia.

Current wake vortex separation minima are a major impediment to increasing air traffic capacity since they are greater than radar separation minima. The concept of dynamic wake vortex separation, which allows reduced separations in favorable weather conditions when wake durations on flight paths become shorter, would allow an increase in capacity. To realize dynamic wake vortex separation, the Japan Aerospace Exploration Agency (JAXA) is developing a wake vortex advisory system (WVAS) that calculates reduced separations that have equal safety to current separations. In addition, JAXA is developing a traffic pattern optimization system (TPOS) that optimizes runway allocation and take-off/landing sequences to maximize airport capacity. An airport traffic simulation indicates that 4.5 percent and 3.4 percent airport capacity gains can be achieved by introducing WVAS and TPOS individually.

Matayoshi, N.

"REDUCED WAKE VORTEX SEPARATION USING WEATHER INFORMATION"

Lecture Notes in Electrical Engineering, Vol. 290, 2014, Springer Japan, pp. 49-68.

Current wake vortex separation minima are a major impediment to increasing traffic capacity since they require greater separations than radar separation minima. The concept of dynamic wake vortex separation, which allows reduced separation in favorable weather conditions when wake durations on flight paths become shorter, would allow an increase in capacity. The Japan Aerospace Exploration Agency (JAXA) has developed a methodology that calculates a reduced wake vortex separation that is equally safe as current separation minima. The methodology uses a probabilistic wake vortex prediction model to probabilistically assure that the wake vortex encounter risks at reduced separations do not exceed those at current separation minima. JAXA has also developed an airport terminal traffic simulation environment to demonstrate the traffic capacity gain at a congested airport when reduced wake vortex separations are introduced and take-off/landing sequences are optimized. The simulation result showed a greater than 10 percent capacity gain, and confirmed the effectiveness of the proposed methodology.

Matayoshi, N.

"DYNAMIC WAKE VORTEX SEPARATION ACCORDING TO WEATHER CONDITIONS"

AIAA Paper 2013-4425, August 2013, Los Angeles, CA.

Current wake vortex separation minima are a major impediment to increasing traffic capacity since they require greater separations than radar separation minima. The concept of dynamic wake vortex separation, which allows reduced separation in favorable weather conditions when wake durations on flight paths become shorter, would allow an increase in capacity. The Japan Aerospace Exploration Agency (JAXA) has developed a methodology that calculates a reduced wake vortex separation that is equally safe as current separation minima. The methodology uses a probabilistic wake vortex prediction model to probabilistically assure that the wake vortex encounter risks at reduced separations do not exceed those at current separation minima. JAXA has also developed an airport terminal traffic simulation environment to demonstrate the traffic capacity gain at a congested airport when dynamic wake vortex separations are introduced and take-off/landing sequences are optimized. The simulation result showed a greater than 10 percent capacity gain, and confirmed the effectiveness of the proposed methodology.

Matayoshi, N. and Okuno, Y.

"EVALUATION OF HELICOPTER ENCOUNTERS WITH WAKE VORTICES"

35th European Rotorcraft Forum, September 2009, Hamburg, Germany.

This paper reports on pilot-in-the-loop flight simulations of helicopter wake vortex encounters conducted by the Japan Aerospace Exploration Agency. To clarify the characteristics of helicopter wake vortex encounters, helicopter responses were compared with those of fixed-wing aircraft in the same conditions. The simulation results indicate that helicopters are less susceptible to wake vortex disturbances than fixed-wing aircraft in the same weight category, with helicopters experiencing half or

less the attitude disturbance and height loss than fixed-wing aircraft. The helicopter pilots consequently felt that there was no risk to flight safety even for encounters at distances somewhat less than the current ICAO wake vortex separation minima. This finding supports the feasibility of reducing wake vortex separation for helicopters compared to fixed-wing aircraft.

Matayoshi, N. and Yoshikawa, E.

"DYNAMIC WAKE VORTEX SEPARATION COMBINING WITH AMAN/DMAN CONCEPT"

AIAA Paper 2015-3397, June 2015, Dallas, TX.

To increase airport capacity, the Japan Aerospace Exploration Agency is developing two technologies: a wake vortex advisory system (WVAS) that calculates reduced wake vortex separations that have equal safety to current separations, and a traffic pattern optimization system (TPOS) that optimizes take-off/landing sequences and runway allocation to increase airport capacity. Based on wake vortex observations of over 3,000 landing aircraft, the dynamic separations of WVAS were verified to be safe and separations could be reduced in 49 percent of cases. The simulation study also revealed that TPOS can reduce delays by 20-70 percent at airports with complex runway layouts by combining TPOS with RECAT. These results indicate that WVAS and TPOS would be effective at increasing airport capacity and reducing delays.

Matayoshi, N., Asaka, K. and Okuno, Y.

"FLIGHT-TEST EVALUATION OF A HELICOPTER AIRBOURNE LIDAR"

Journal of Aircraft, Vol. 44, No. 5, September-October 2007, pp. 1712-1720.

The Japan Aerospace Exploration Agency has conducted ground and flight-test evaluation of a prototype 1.5-micron all-fiber pulsed coherent Doppler lidar produced by Mitsubishi Electric Corporation, which aims to measure three-axis components of airspeed and detect atmospheric turbulence ahead of a helicopter. In the ground test, the lidar has proven its capability to detect atmospheric turbulence with a scale of several tens of meters by accurately measuring helicopter rotor downwash. In the flight test, the lidar was installed in the Japan Aerospace Exploration Agency's MuPAL-e research helicopter and the accuracy of real-time airspeed calculation using lidar outputs and the format of a real-time pilot display were evaluated. The lidar successfully measured three-axis airspeed components accurately even in low-airspeed flight regimes including hovering, backwards, and sideways flight where the conventional pitot-static system does not work and its capability as a helicopter airspeed sensor was proven. Some technical challenges were found for atmospheric turbulence detection, such as increasing the detection range and improving the data analysis and presentation. These results will be used to establish the specifications of practical airbourne lidars.

Matayoshi, N., Okuno, Y., Sugiura, M., Kono, M., Yoshii, T. and Hirata, T.

"AIRPORT TERMINAL TRAFFIC SIMULATION APPLYING REDUCED WAKE VORTEX SEPARATION"

AIAA Paper No. 2010-9338, September 2010, Fort Worth, TX.

The Japan Aerospace Exploration Agency has developed an airport terminal traffic simulation environment that dynamically minimizes aircraft wake vortex separation by considering wake vortex behaviors from meteorological information and using GBAS-based curved approach paths. A traffic simulation of Tokyo International airport using four intersecting runways revealed that the capacity could be increased by up to 12 percent by reducing separations without additional risk of wake vortex encounter. This result demonstrates the benefit to airport capacity of reducing wake vortex separations dynamically.

Matayoshi, N., Yoshikawa, E. and Yamamoto, M.

"WAKE VORTEX MEASUREMENT USING PULSED DOPPLER LIDAR"

19th Coherent Laser Radar Conference (CLRC), Paper Th6, June 2018, Okinawa, Japan.

The Japan Aerospace Exploration Agency (JAXA) developed the original algorithm to detect wake vortex shed from aircraft using spectral data of pulsed Doppler lidar. The JAXA has been conducting the wake vortex measurement at two major airports in Japan using a pulsed Doppler lidar and demonstrated the capability of extracting wake characteristics including wake position and circulation strength from lidar spectral data. The acquired wake characteristics will be used to support safe and efficient aircraft operations.

Mather, G. K.

"A NOTE ON SOME MEASUREMENTS MADE IN VORTEX WAKES BEHIND A DC-8"

National Research Council (Canada), Division of Mechanical Engineering and National Aeronautical Establishment, Quarterly Bulletin, No. 2, 1967, pp. 45-54

A discussion of measurements of maximum circumferential velocities obtained by the NAE T-33 when flying 3500 and 1000 feet directly behind a DC-8, seeking the wing tip vortices. It is found that the measured maximum velocities of these vortices are substantially higher than those predicted by accepted theory. No reduction in vortex strength due to dissipative effects was observed.

Mathias, D. L., Ross, J. C. and Cummings, R. M.

"WAKE INTEGRATION TO PREDICT WING SPAN LOADING FROM A NUMERICAL SIMULATION"

J. Aircraft, Vol. 32, No. 5, Sept.-Oct. 1995, pp. 1165-1167

A new method of computing the spanwise lift distribution and induced drag from a CFD solution was developed. An equivalent lifting line model is created by integrating the circulation in the wake and it is used for loads computation. The method was applied to a simple, rectangular wing configuration, and the difference in lift and induced drag coefficients between computation and experiment was less than

3 and 5%, respectively. Results indicate that this method offers a simple alternative to computing lift and induced drag by pressure integration.

Mathias, D. L., Roth, K. R., Ross, J. C., Rogers, S. E. and Cummings, R. M.

"NAVIER-STOKES ANALYSIS OF THE FLOW ABOUT A FLAP EDGE"

J. Aircraft, Vol. 35, No. 6, November-December 1998, pp. 833-838

The current study computationally examines one of the principal three-dimensional features of the flow over a high-lift system, the flow associated with a flap edge. Structured, overset grids were used in conjunction with an incompressible Navier-Stokes solver to compute the flow over a two-element high-lift configuration. The computations were run in a fully turbulent mode using the one-equation Baldwin-Barth model. Specific emphasis was given to the details of the flow in the vicinity of the flap edge, and so the geometry was simplified to isolate this region. The geometry consisted of an unswept wing, which spanned a wind-tunnel test section, equipped with a single-element flap. Two flap configurations were computed: a full-span and a half-span Fowler flap. The chord-based Reynolds number was $3.7 \times 1,000,000$ for all cases. The results for the full-span flap agreed with two-dimensional experimental results and verified the method. Grid topologies and related issues for the half-span flap geometry are discussed. Results of the half-span flap case are compared with three-dimensional experimental results, with emphasis on the flow features associated with the flap edge. The results show the effect of the vortex created by the flap edge, including the impact on flow separation and spanwise lift distribution.

Matos, C., Reddy, U. and Komerath, N.

"ROTOR WAKE/FIXED WING INTERACTIONS WITH FLAP DEFLECTION"

55th Annual Forum of the American Helicopter Society, May 1999, Montreal, Canada.

The basic features in the interaction of a rotor wake with a wing in low-speed forward flight are studied using low-speed wing tunnel experiments. The configuration captures several of the aerodynamic interactions in the tiltrotor transition phase, and during wake/empennage interactions. Previous work showed that the pressure field on the wing surface below the rotor is dominated by n-per-rev 'blade passage', while the velocity field is dominated by once-per-rev repetition of the vortex geometry, due to vortex interactions. The effect of deflecting trailing edge flaps is studied here. Large area Spatial Correlation Velocimetry is used to enable velocity field acquisition at various sections and test conditions. Flap deflection modifies the spanwise flow on the wing surface, and causes an apparent lateral shift in the wake interaction. This shift influences the effectiveness of inboard vs. outboard flaps, and opens possibilities for augmenting rolling moments. The paper describes both a unique capability for scanning several cross-sections of a periodic velocity field during such interaction

conditions, and the correlation of data from velocity, pressure, and force measurements to synthesize the nature of the complex flowfield with its multiple periodicities.

Matsumoto, Y., Ueno, K. and Saito, T.

"A MOMENT MODEL WITH VARIABLE LENGTH SCALE FOR THE MOTION OF A VORTEX PAIR IN TWO-DIMENSIONAL INCOMPRESSIBLE FLOWS"

Physics of Fluids, Vol. 21, 2009, pp. 047103-1 to 047301-11.

A simple model for the motion of a vortex pair in two-dimensional inviscid flows is presented. In this model the motion of the vortex pair is expressed by a set of ordinary differential equations for the dipole moment, the length scale, and the centroid position. The length scale is the distance between the positive vortex and the negative vortex in the pair. A self-propelling velocity of the model vortex pair is introduced in response to a wide range of the length scale. If a background flow is a linear function of the position, the dipole moment and the length scale of the model are exact. This model works well for a separated vortex pair, although it is not applicable to an asymmetrically deformed vortex pair.

Matsushima, K. and Kato, H.

"NUMERICAL ASSESSMENT FOR PIV PRESSURE MEASUREMENTS IN AIRPLANE WAKES"

AIAA Paper 2016-3270, June 2016, Washington, DC.

A pressure estimation system which uses a new model of a Poisson equation and isentropic boundary conditions has been examined. The primary objective of the system is to let stereo PIV measurement more advantageous for a wake survey in aerodynamic design of aircraft. In the wake plane, aerodynamic quantities such as velocity, pressure are no longer two dimensional, then common methods of in-plane two-dimensional (2D) PIV pressure calculation do not work. That is why the new model called two and a half dimensional (2.5D) one has been developed for the system. In this article, the accuracy of estimated pressure by the system is examined for both subsonic and transonic flows. Then, in the view point of its ability for practical application, the effect of measurement velocity fluctuation is simulated on pressure estimation. All the examinations are done by computer simulation, where, instead of PIV measurement velocity data, those of CFD simulation results are used. The results show that the 2.5D model and isentropic boundary conditions work well for both subsonic (incompressible) flows and transonic (compressible) ones. It is also shown the proposed system has good ability to estimate pressure distribution on the PIV measurement plane with less than one percent error if the velocity data have five percent fluctuation.

Matsushima, K., Namba, R. and Kato, H.

"PRESSURE ANALYSIS BASED ON PIV MEASUREMENT IN AIRPLANE WAKES"

ICAS-2016-0594, September 2016, Daejeon, Korea.

A pressure estimation system which uses the two and a half dimensional (2.5D) form of a Poisson equation and isentropic boundary conditions has been applied to a variety of flows. The primary objective of the system is to let stereo PIV measurement more advantageous for a wake survey in aerodynamic design of aircraft and other transport. In wakes, velocity and pressure distributions are no longer two dimensional, then common methods of in-plane two-dimensional (2D) PIV pressure calculation do not work. The accuracy of estimated pressure by the system is investigated for both subsonic and transonic flows around a wing. The results show that the 2.5D model and isentropic boundary conditions work well for both subsonic (incompressible) flows and transonic (compressible) ones. Then, the system is applied to PIV measurement for the wake of a practical automobile. It works well, too, and indicates great promise as a non-intrusive pressure measurement method.

Mattei, A. and Santoro, E.

"NUMERICAL COMPUTATIONS OF WAKE VORTICES BEHIND LIFTING SURFACES"

International Council of the Aeronautical Sciences Paper 74-28, Haifa, Israel, 1974

A numerical method is developed for the calculation of the wake vortices behind lifting wings. According to modern three-dimensional methods, discrete vortices are distributed on the camber surface of the wing and upon the wake. The rolled-up vortex sheet is obtained by a convergent interactive procedure. Different numerical schemes investigated are compared for obtaining smooth solutions and minimizing computer time.

Matthews, M. P. and Denneno, A. P.

"INTEGRATION OF MULTIPLE METEOROLOGICAL SENSOR OBSERVATIONS FOR WAKE VORTEX BEHAVIOR COMPARISON"

Proceedings of the 8th Conference on Aviation, Range, and Aerospace Meteorology, Dallas, TX, January 1999

The hazard that wake turbulence presents to following aircraft while operating in the terminal area requires the use of minimum separations between aircraft on final approach. In Instrumented Flight Rules conditions this can be a significant constraint on the airport arrival rate. The National Aeronautics and Space Administration (NASA) Langley Research Center has been researching the development of the Aircraft Vortex Spacing System (AVOSS), which would dynamically change aircraft arrival separations based upon atmospheric conditions and an understanding of vortex behavior (Hinton, 1995). As part of this effort, a collection of meteorological sensor systems have been deployed by Lincoln Laboratory and NASA Langley at the Dallas/Fort Worth International Airport (Matthews, et al., 1997). These sensors, along with many existing FAA and NWS systems, are used to create profiles of the atmosphere at the DFW airport. The suite of sensors available for wake vortex comparison include a Radian LAP-3000 profiler, two Remtech PA-2 sodars, a 150-foot instrumented tower, two nearby Terminal Doppler Weather Radars, and the NWS sounding at Fort Worth. The greatest challenge in the

collection of all this meteorological information is preparing a single atmospheric profile for the wake vortex behavior models. In post-processing, a human can interpret all of the data and create a profile based upon known sensor limitations and analysis of the data. However, a future AVOSS system will require real-time atmospheric profiles representing the state of the atmosphere to apply the wake vortex behavior models. To do this, an automated algorithm is required to perform the data quality editing and data fusion of sensor data. This paper is an overview of the sensor systems available to the wake vortex behavior algorithms and the AVOSS Winds Analysis System that performs the automated data editing and fusion of the atmospheric winds at the Dallas/Fort Worth Airport.

Matthews, M. P., Dasey, T. J., Perras, G. H. and Campbell, S. D.

"PLANETARY BOUNDARY LAYER MEASUREMENTS FOR THE UNDERSTANDING OF AIRCRAFT WAKE VORTEX BEHAVIOR"

Proc. Seventh Conf. on Aviation, Range and Aerospace Meteorology, American Meteorological Society, Boston, MA, February 1997, pp. 175-180

This paper described a comprehensive method of collecting meteorological and wake vortex data in an operational airport environment. A method for analyzing the meteorological data for creation of atmospheric profiles was discussed. An example of the meteorological and wake vortex data was shown. Results for this case show that the lateral motion of the wake vortices is closely linked to the crosswind component from the atmospheric winds. Also, the data shown supports the theory that the descent rate and decay rate of the vortex can be influenced by the atmospheric stability. Future work will include more detailed analysis, as well as moving the instrumentation suite from Memphis to the Dallas/Ft. Worth International Airport in the winter of 1997.

Mauel, S.

"FRANKFURT AIRPORT CAPACITY ENHANCEMENT PROGRAM: THE ROLE OF WAKE VORTEX REDUCING MEASURES"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

In 2003, Frankfurt Airport registered 458,865 movements, dealing with over 48 million passengers and 1.5 million tons of cargo. The airport will reach its capacity limit in 2006. Work is underway for the construction of a fourth runway (for landings only) and a third terminal by 2013. Key to the development and implementation of capacity enhancement systems is the handling of wake vortex separations. Three potential solutions are being addressed. First, measures to predict the occurrence of wake vortices (Wake Vortex Warning System with its Wind Temperature Radar). Second, measures to avoid wake vortex encounters (High Approach Landing System with Dual Threshold Operation). Third, measures to reduce the minimum radar separation between two medium aircraft (Precision Approach Monitoring). To date, the High Approach Landing System (HALS) has been tested successfully; the ongoing development of the Dual Threshold Operation is to overcome the procedural

deficits of HALS. The technology to reduce the minimum radar separation has been tested successfully, but the decision to install an operational system and procedures has not yet been taken.

Maurice, M. S.

"LASER VELOCIMETRY SEED PARTICLES WITHIN COMPRESSIBLE, VORTICAL FLOWS"

AIAA Journal, Vol. 30, No. 2, February 1992, pp. 376-383.

The ability of seed particles to penetrate and accurately track vortices is of critical importance to the analysis of laser velocimetry (LV) measurements within these flow structures. In applying a particle equation of motion to vortical flowfields which extend into the supersonic, compressible regime, two approaches are considered. First, an ideal, potential vortex is developed for a compressible flowfield. As an aid to the design and analysis of vortical flowfield surveys over a wide range of independent parameters, this model is used to plot the time and position at which any particle starting at rest within a vortex will begin to track the flow velocity within 3% error. As a specific application, the potential vortex is then used to estimate the dynamic bias of LV measurements taken within a vortex shed from a 75-deg delta wing at 20 deg angle of attack in a Mach 1.9 supersonic flow. The second approach uses a computationally derived Navier-Stokes flowfield solution in place of the potential vortex model. The computational flowfield method predicts that accurate LV measurements within the delta wing flowfield require seed particles no larger than 0.1-0.2 microns in diameter, and defines the unseeded inner vortex core region. Both approaches show an increase in velocity bias which is nearly proportional to particle diameter, stressing the need for a monodisperse seed of known size to resolve particle bias in complex flows.

Maxworthy, T.

"TURBULENT VORTEX RINGS"

Journal of Fluid Mechanics, Vol. 64, part 2, 1974, pp. 227-239.

We consider the motion of the mass of fluid ejected through a sharp-edged orifice by the motion of a piston. The vorticity formed by viscous forces within the separated flow at the sharp edge rolls up to form a concentrated vortex which, after a development period, consists of a core of very fine scale turbulence surrounded by a co-moving bubble of much larger scale turbulence. This bubble entrains outer fluid, mixes with it, and deposits the majority into a wake together with some small fraction of the total vorticity of the ring. Enough fluid is retained to account for the slow growth of the whole fluid mass. A theory which takes account of both the growth process and the loss of vorticity is proposed. By comparison with experimental measurements we have determined that the entrainment coefficient for turbulent vortex rings has a value equal to 0.011 ± 0.001 , while their effective drag coefficient is 0.09 ± 0.01 . These results seem to be independent of Reynolds number to within experimental accuracy.

Maxworthy, T.

"SOME EXPERIMENTAL STUDIES OF VORTEX RINGS"

Journal of Fluid Mechanics, Vol. 81, part 3, 1977, pp. 465-495.

A series of experiments designed to reveal the properties of high Reynolds number vortex rings, using flow-visualization and laser-Doppler techniques, has uncovered several interesting and unexpected results. Starting at the beginning of the motion, at a nozzle, and proceeding downstream, these include the following. (i) A formation process that is strongly Reynolds number dependent. (ii) The amount of vorticity that appears downstream is very close to that predicted by a simple 'slug' model. However, flow-visualization studies show that such a model is an oversimplification and that an excess of ring vorticity is probably cancelled by the ingestion of vorticity of opposite sign at the nozzle lip. (iii) A new, bimodal form of vortex-core instability has been observed at moderate but not high Reynolds numbers. (iv) Azimuthal inhomogeneities in the breaking of these, and the normal instability waves, create an 'axial' flow along the vortex core in the turbulent ring. This axial flow takes the form of a propagating wave that has many characteristics of a solitary wave. It is hypothesized that this axial flow prevents further ring instability. (v) The long-term behavior of the turbulent ring is marked by dramatic changes in its growth rate, which are probably related to changes in the 'organization' of the vortex core. The descriptive turbulent-ring model developed in Maxworthy (1974) is substantially confirmed by these experiments and by observation of ring propagation through a stratified fluid.

Maxworthy, T.

"THE STRUCTURE AND STABILITY OF VORTEX RINGS"

J. Fluid Mech., Vol. 51, Part 1, 1972, pp. 15-32

A series of observations on experimentally produced vortex rings is described. The flow field, ring velocity and growth rate were observed using dye and hydrogen-bubble techniques. It was found that stable rings are formed and grow in such a way that most of their vorticity is distributed throughout a fluid volume which is larger than and moving with the visible dye core. As the vorticity diffuses out of this moving body of fluid into the outer irrotational fluid, it has two effects. It causes some of the fluid, with newly acquired vorticity, to be entrained into the interior of the bubble, while the rest is left behind and accounts for the appearance of ring vorticity in a wake. It was found that the velocity of translation U of these stable rings varies as t^{-1} , at high Reynolds number, where t is the time measured from the start of the motion at a virtual origin at downstream infinity. A simple theoretical model is presented which explains all these features of the observed stable flow. Rings of even higher Reynolds number become unstable and shed significantly more vorticity into the wake. Under some circumstances a new more stable vortex emerges from this shedding process and continues with less vorticity than before. Eventually, the ring motion ceases as all of its vorticity is deposited into the wake and is spread by viscous diffusion. Observations of the interaction between two nearly identical rings travelling a common path showed that, contrary to popular belief, rings do not pass back and forth through one another, but that the rearward one becomes entrained into the forward one. Only when

the rearward ring has a much higher velocity than its partner can it emerge from the joining process and leave a slower-moving ring behind.

Maxworthy, T.

"THE MOTION OF AIRCRAFT TRAILING VORTICES"

J. Applied Mechanics, Vol. 42, No. 2, June 1975, pp. 279-282

Knowledge of the motion of turbulent vortex rings is used to speculate upon the dynamical characteristics of the trailing vortex pair which forms the wake of a lifting surface. An interpretation is presented of common observations which suggests that the gross features of the two systems are similar, at least before the aircraft wake distorts due, among other things, to a self-induced instability. The theory presented by Maxworthy (1974) is extended to the two-dimensional case and predictions of the shape of aircraft trails are displayed in nondimensional form. As a special case a preliminary prediction is given for the wake shape of a 747, in cruise condition, for a set of parameters that are only approximately correct. Only comparison with actual observations can further refine these guesses.

Maxworthy, T.

"WAVES ON VORTEX CORES"

Fluids Dynamics Research, Vol. 3, Issues 1-4, Sept.1988, pp. 52-62

Here we discuss the types of waves which can be supported on compact regions of vorticity. This is a subject first studied by Lord Kelvin for waves propagating along the vortex lines of the Rankine and hollow-core vorticity distributions. Kelvin's major interest was in the stability of vortex rings and the numerous resurgences in interest have usually been driven by practically important phenomena, e.g., the observations of vortex breakdown and waves on tornado and aircraft vortices in the early 1960's and more recently in technologically and geophysically significant flows and on the quantized vortices of super fluid Helium. The major wave-types of interest are of varicose, helicoidal and fluted form and represent a periodic swelling and contraction, a bending and a 'krinkling' of the core, respectively. The first two propagate along and the third around the vortex lines. All have been studied theoretically, experimentally, and numerically in the limit of small wave amplitude and their major characteristics are now clear. Of particular interest is the extension of these results to the non-linear regime in which case the two first types are known to exhibit solitary wave or dominate observations of vortex flows both in nature and in technological applications and which have caused much controversy in the interpretation of results found under complex circumstances of flow and apparatus geometry.

May, D. H. and Vatsistas, G. H.

"TIP VORTEX DEPENDENCE WITH ANGLE OF ATTACK"

Journal of Aircraft, Vol. 43, No. 5, September-October, 2006, pp. 1582-1585

An analysis that explains the dependence of the tip vortex characteristics and their variation with angle of attack and downstream distance, under certain conditions, has been detailed. First, the low wing loading analysis of Moore and Saffman is used as the asymptotic far-field regime. Dimensional analysis presents reasoning for a hypothetical near field. A balance of these two scaling laws is made and is shown to apply in an intermediate-field regime. In the intermediate field, various vortex characteristics are shown to vary as a logarithmic variation with angle of attack. The expressions obtained are shown to hold for some peak tangential velocity data. An expression coupling the circulation and the core radius is obtained. This is used to obtain an expression for the axial vorticity; under the assumption of constant total pressure losses over a range of angle of attack, the expression obtained is shown to agree with some experimental data.

May, N.

"RUNWAY CAPACITY CONSTRAINTS AT HEATHROW AIRPORT"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

The capacity of Heathrow Airport is constrained by the capacity of the two runways. In recent years, many steps have been taken to increase runway capacity but these have been able to produce only small, incremental increases rather than the large, step change increases demanded by the aviation industry. One of the major constraints on runway capacity is the separation required between successive arrivals or between successive departures. These separations are governed in part by the wake vortex separations necessary to ensure the safety of arriving and departing aircraft. The presentation described the process used by NATS to declare runway capacity at Heathrow and identified the factors that constrain increases to that capacity. Particular focus was placed on one of these factors, namely the wake vortex separations between aircraft. Examples were provided that illustrate the potential capacity gains that could be achieved from safely reducing the required separations between aircraft. There was also a discussion around the operational tactics employed by controllers at Heathrow to minimize the effects of wake vortex separations on runway capacity.

Maybey, D. G.

"REVIEW OF AIRCRAFT DYNAMIC LOADS DUE TO FLOW SEPARATION"

Proceedings of Fluid Dynamic Panel Symposium, Vortex Flow Aerodynamics, AGARD, CP-494, Scheveningen, The Netherlands, October 1990, pp. 12-1 to 12-10

This paper presents a detailed review of the 70th meeting of the AGARD Structures and Materials Panel, prepared for the AGARD Fluid Dynamics Panel. Accordingly, emphasis is placed on the Aerodynamic information presented, rather than on the Structural Aspects. Experimental results and computations are described for flows with bubble and vortex separations. Some conclusions are drawn and recommendations are made for further research. In particular, the review suggests that much

greater attention should be given to establishing the magnitude of possible scale effects (both in experiments and calculations) and to the prediction of fin buffeting.

Mayer, E. W. and Powell, K. G.

"SIMILARITY SOLUTIONS FOR VISCOUS VORTEX CORES"

Journal of Fluid Mechanics, Vol. 238, 1992, pp. 487-507.

Results are presented for a class of self-similar solutions of the steady, axisymmetric Navier-Stokes equations, representing the flows in slender (quasi-cylindrical) vortices. Effects of vortex strength, axial gradients and compressibility are studied. The presence of viscosity is shown to couple the parameters describing the core growth rate and the external flow field, and numerical solutions show that the presence of an axial pressure gradient has a strong effect on the axial flow in the core. For the viscous compressible vortex, near-zero densities and pressures and low temperatures are seen on the vortex axis as the strength of the vortex increases. Compressibility is also shown to have a significant influence upon the distribution of vorticity in the vortex core.

Mayer, E. W. and Powell, K. G.

"VISCOUS AND INVISCID INSTABILITIES OF A TRAILING VORTEX"

J. Fluid Mech., Vol. 245, December 1992, pp. 91-114

A spectral collection and matrix eigenvalue method is used to study the linear stability of the trailing line vortex model of Batchelor. For both the inviscid and viscous stability problem, the entire unstable region in the swirl/axial wavenumber parameter space is mapped out for various azimuthal wavenumbers m . In the inviscid case, the non-axisymmetric perturbation with azimuthal wavenumber $m=1$ has an unstable region of larger extent than any other, with an unusual two-lobed structure; also, the location and numerical value of the maximum disturbance growth rate previously reported for this case are shown to be incorrect.

Mayer, R. H.

"ANALYSIS OF POTENTIAL BENEFITS OF WIND DEPENDENT PARALLEL ARRIVAL OPERATIONS"

24th Digital Avionics Systems Conference, Vol. 1, Nov. 2005, pp. 2.B.6-1-2.B.6-12

This paper documents the results of fast-time simulations evaluating potential capacity benefits of procedure concepts developed for parallel approaches to Closely Spaced Parallel Runways (CSPR) at airports with runway spacing less than 2,500 feet. Currently, simultaneous arrival operations at CSPR airports rely on visual meteorological conditions (VMC). In inclement weather when visual procedures can no longer be applied, simultaneous arrivals must be discontinued. Application of standard aircraft separations based on Instrument Flight Rules (IFR) effectively results in the loss of arrival operations on one of the two runways, significantly reducing the arrival capacity of CSPR airports. Proposed wind-

dependent parallel approach concepts promise improvements in arrival capacity at CSPR airports by enabling continued operations of dual arrival streams in instrument meteorological conditions (IMC). The concepts permit dependent parallel arrival operations when meteorological conditions are determined to render approach paths free of wake vortices from preceding aircraft. The operations are expected to increase capacity during IMC and decrease weather-related delays at CSPR airports. Simulation results for 9 CSPR airports in the National Airspace System (NAS) suggest significant potential capacity benefits ranging from 2 to 18 additional arrival operations per hour depending upon the concept and airport. The paper outlines the proposed wake independent straight-in parallel approach concept and 12 procedural derivatives. It describes the model developed to visualize the operations and the Monte Carlo approach taken to quantify potential capacity benefits.

Mazourov, G. I., Akselevich, V. I. and Al-Nabolsy, T.

"THE ESTIMATION OF IMPACT AIRCRAFT WAKE VORTICES ON FLIGHT AND WAYS TO IMPROVE THEIR FORECAST"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000.

Aircraft wake vortices are one of the new and little well-known phenomena in the atmosphere. Our research includes the results of numerical, laboratory and natural experiments and allows us to define 8 similar types of fog and cloudy formations which are connected with this effect. Some of them as condensation tracks behind planes, cloudy tracks behind helicopters and cloudy bands behind marine courts have many common features. In poster describes the favorable aero meteorological conditions of appearance of aircraft wake vortices and the opportunities of their impact on aircraft flights. The natural experiments show the intensive circulation in closed contour at the track behind the transport mean. Because the helicopters fulfill the flights on small and extremely small heights, the appearance of cloudy tracks are decreasing the visibility. It's very dangerous to flight safety. Instead of this we can see cloudy bands also behind the marine courts. Its effects were found by meteorological artificial satellites of the Earth. The natural experiments on the Black and Baltic Sea help us to understand some causes of the track's appearance. We also spent the laboratory experiment in aerodynamical tube and numerical modelling of describing the effect. The second dangerous phenomenon which is connected with aircraft vortices is the strong turbulence. Especially its impact on flights of aircraft at marine courts. The big attention relates methods of forecasting the cloudy tracks. The important place has the classification of tracks and the comparison of impact high described phenomena on aircraft flights.

Mazurin, N. F. and Kulizhnikova, L. K.

"INTERCOMPARISON OF INSTRUMENTS FOR MEASUREMENTS OF THE ATMOSPHERIC TURBULENCE CHARACTERISTICS"

Russian Meteorology and Hydrology, Vol. 33, No. 11, 2008, pp. 743-747.

In this paper, intercomparison testing of the Wind Master sonic anemometer manufactured by Gill Instruments Ltd. (U.K.) and two sonic anemometers manufactured by the Taifun Scientific Industrial

Association (Obninsk, Russia), ATsAT-3M are described. Data of measurements of the standard deviations and spectrum characteristics of the vertical and horizontal wind speed components, heat and friction fluxes are presented. Dispersion of the measurements and degree of their coherence are characterized by the regression equation coefficients (a and b) and the cross-correlation coefficients. The coherence plot shows compliance of the measurements data throughout the entire frequency range.

Mba, M. N., Favier, D. and Maresca, C.

"AN EXPERIMENTAL AND NUMERICAL STUDY OF 3-D ROTOR WAKES IN HOVERING FLIGHT"

ICAS 1982, August 1982, Seattle, WA.

Results of comparison between experimental and numerical studies on the 3-D wake of a hovering rotor are presented. The wind-tunnel investigation is conducted by means of X-hot wires and laser Doppler anemometry procedures to measure the 3-D velocity field under the rotor and to determine the tip vortex paths for several rotor configurations. Additional flow visualization and rotor air load coefficients are also carried out. The prediction model is based on the classical vortex theory with an empirically prescribed geometry of the wake. From the blade circulation distribution, the rotor wake is represented by vortex lines which are allowed to freely adapt until a converged wake geometry is obtained. Then a new estimate of the blade circulation repartition can be deduced. The procedure is repeated, iterating until the compatibility between the adapted wake geometry and the blade circulation repartition is obtained. The validity range of the circulation model is deduced from comparison with experimental data obtained on instantaneous velocities and tip vortex paths, for different rotor parameters including solidity, number of blades, pitch angle, blade twist, and tip shape.

Mba, M. N., Favier, D. and Maresca, C.

"3-D WAKE OF A HOVERING ROTOR"

13th International Council of Aeronautical Sciences Congress and AIAA Aircraft Systems and Technology Conf., Seattle, WA, August 1982, pp. 689-699

Results of comparison between experimental and numerical studies on the 3-D wake of a hovering rotor are presented. The wind-tunnel investigation is conducted by means of X-hot wires and laser Doppler anemometry procedures to measure the 3-D velocity field under the rotor and to determine the tip vortex paths for several rotor configurations.

McAlister, K.

"MEASUREMENTS IN THE NEAR WAKE OF A HOVERING ROTOR"

AIAA Paper No. 1996-1958, New Orleans, LA, June 1996

Primarily an experimental effort, this study focuses on the velocity and vorticity fields in the near wake of a hovering rotor. Drag terminology is reviewed, and the theory for separately determining the profile- and induced-drag components from wake quantities is introduced. Instantaneous visualizations of the flow field are used to center the laser velocimeter measurements on the vortex core and to assess the extent of the positional meandering of the trailing vortex. Velocity profiles obtained at different rotor speeds and distances behind the rotor blade clearly indicate the position, size, and rate of movement of the wake sheet and the core of the trailing vortex. The results also show the distribution of vorticity along the wake sheet and within the trailing vortex.

McAlister, K. W.

"ROTOR WAKE DEVELOPMENT DURING THE FIRST REVOLUTION"

American Helicopter Society 59th Annual Forum, May 2003, Phoenix, AZ.

The wake behind a two-bladed model rotor in light climb was measured using particle image velocimetry, with particular emphasis on the development of the trailing vortex during the first revolution of the rotor. The distribution of vorticity was distinguished from the slightly elliptical swirl pattern. Peculiar dynamics within the 'void' region may explain why the peak vorticity appeared to shift away from the center as the vortex aged, suggesting the onset of instability. The swirl and axial velocities (which reached 44 and 12 percent of the rotor-tip speed, respectively) were found to be asymmetric relative to the vortex center. In particular, the axial flow was composed of two concentrated zones moving in opposite directions. The radial distribution of the circulation rapidly increased in magnitude until reaching a point just beyond the core radius, after which the rate of growth decreased significantly. The core-radius circulation increased slightly with wake age, but the large-radius circulation appeared to remain relatively constant. The radial distributions of swirl velocity and vorticity exhibit self-similar behaviors, especially within the core. The diameter of the vortex core was initially about 10 percent of the rotor-blade chord, but more than doubled its size after one revolution of the rotor. According to vortex models that approximate the measured data, the core-radius circulation was about 79 percent of the large-radius circulation, and the large-radius circulation was about 67 percent of the maximum bound circulation on the rotor blade. On average, about 53 percent of the maximum bound circulation resides within the vortex core during the first revolution of the rotor.

McAlister, K. W.

"ROTOR WAKE DEVELOPMENT DURING THE FIRST REVOLUTION"

J. American Helicopter Soc., Vol. 49, Oct. 2004, pp. 371-390

The wake behind a two-bladed model rotor in a shallow climb was measured using particle image velocimetry. The distribution of vorticity was distinguished from the slightly elliptical swirl pattern. Peculiar dynamics within the 'void' region were found to accompany a shift in the peak vorticity away from the center as the vortex aged. The swirl and axial velocities (that reached 44 and 12 percent of

the rotor-tip speed, respectively) were found to be asymmetric relative to the vortex center. In particular, the axial flow was composed of two concentrated zones moving in opposite directions. The radial distributions of swirl velocity and vorticity exhibit self-similar behaviors, especially within the core. The diameter of the vortex core was initially about 10 percent of the rotor-blade chord, but more than doubled its size after one revolution of the rotor. According to vortex models that approximate the measured data, the core-radius circulation was about 79 percent of the large-radius circulation, and the large-radius circulation was about 67 percent of the maximum bound circulation on the rotor blade. On average, about 53 percent of the maximum bound circulation resides within the vortex core during the first revolution of the rotor.

McAlister, K. W. and Heineck, J. T.

"MEASUREMENTS OF THE EARLY DEVELOPMENT OF TRAILING VORTICITY FROM A ROTOR"

NASA TP-2002-211848, AFDD/TR-02-A-001, July 2002, Army/NASA Rotorcraft Division, Moffett Field, CA

The wake behind a two-bladed model rotor in light climb was measured using particle image velocimetry, with particular emphasis on the development of the trailing vortex during the first revolution of the rotor. The distribution of vorticity was distinguished from the slightly elliptical swirl pattern. Peculiar dynamics within the 'void' region may explain why the peak vorticity appeared to shift away from the center as the vortex aged, suggesting the onset of instability. The swirl and axial velocities (which reached 44 and 12 percent of the rotor-tip speed, respectively) were found to be asymmetric relative to the vortex center. In particular, the axial flow was composed of two concentrated zones moving in opposite directions. The radial distribution of the circulation rapidly increased in magnitude until reaching a point just beyond the core radius, after which the rate of growth decreased significantly. The core-radius circulation increased slightly with wake age, but the large-radius circulation appeared to remain relatively constant. The radial distributions of swirl velocity and vorticity exhibit self-similar behaviors, especially within the core. The diameter of the vortex core was initially about 10 percent of the rotor-blade chord, but more than doubled its size after one revolution of the rotor. According to vortex models that approximate the measured data, the core-radius circulation was about 79 percent of the large-radius circulation, and the large-radius circulation was about 67 percent of the maximum bound circulation on the rotor blade. On average, about 53 percent of the maximum bound circulation resides within the vortex core during the first revolution of the rotor.

McAlister, K. W. and Takahashi, R. K.

"NACA 0015 WING PRESSURE AND TRAILING VORTEX MEASUREMENTS"

NASA TP-3151, November 1991, NASA Ames Research Center, Moffett Field, CA

A NACA 0015 semispan wing was placed in a low-speed wind tunnel, and measurements were made of the pressure on the upper and lower surface of the wing and of the velocity across the vortex trailing downstream from the tip of the wing. A two-component laser velocimeter was used to measure

velocity profiles across the vortex at numerous stations behind the wing and for various combinations of conditions. These conditions include three aspect ratios, three chord lengths, a square- and a round-lateral tip, presence or absence of a boundary-layer trip, and three image plane positions located opposite the wing tip. The addition of a round-lateral edge to the wing tip was found to eliminate the secondary vortex near the wing tip, but had little effect on the downstream characteristics of the trailing vortex.

McAlister, K. W., Huang, S. S. and Abrego, A. I.

"A MODEL ROTOR IN AXIAL FLIGHT"

NASA/TM-2001-210925, AFDD/TR-01-A-004, July 2002, Army/NASA Rotorcraft Division, Moffett Field, CA

A model rotor was mounted horizontally in the settling chamber of a wind tunnel to obtain performance and wake structure data under low climb conditions. The immediate wake of the rotor was carefully surveyed using 3-component particle image velocimetry to define the velocity and vortical content of the flow, and the data used in a subsequent study to validate a theory for the separate determination of induced and profile drag. Measurements were obtained for two collective pitch angles intended to render a predominately induced drag state and another with a marked increase in profile drag. A majority of the azimuthally directed vorticity in the wake was found to be concentrated in the tip vortices. However, adjacent layers of inboard vorticity with opposite sense were clearly present. At low collective, the proximity of the tip vortex from the previous blade caused the wake from the most recent blade passage to be distorted. The deficit velocity component that was directed along the azimuth of the rotor blade was never more than 15% of the rotor tip speed, and except for the region of the tip vortex, appeared to have totally disappeared from the wake left by the previous blade.

McAlister, K. W., Tung, C. and Heineck, J. T.

"DEVICES THAT ALTER THE TIP VORTEX OF A ROTOR"

NASA/TM-2001-209625, AFDD/TR-01-A-003, February 2001, Aeroflightdynamics Directorate, US Army Aviation and Missile Command, Ames Research Center, Moffett Field, CA

Small devices were attached near the tip of a hovering rotor blade to alter the structure and trajectory of the trailing vortex. Stereo particle image velocimetry (PIV) images were used to quantify the wake behind the rotor blade during the first revolution. A procedure for analyzing the 3D-velocity field is presented that includes a method for accounting for vortex wander. The results show that a vortex generator can alter the trajectory of the trailing vortex and that a major change in the size and intensity of the trailing vortex can be achieved by introducing a high level of turbulence into the core of the vortex.

McAlister, K. W., Tung, C. and Heineck, J. T.

"ALTERING THE TIP VORTEX OF A ROTOR"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Small devices were placed near the tip of a hovering rotor blade to alter the structure of the trailing vortex. This was achieved through the generation of either a secondary vortex (positive or negative sense) or massive turbulence. The impact of these devices on the primary trailing vortex during the first revolution was quantified using detailed three-component presentations of the rotor wake obtained with a stereo particle image velocimeter. Even without a device attached to the rotor, the trailing vortex wandered from revolution to revolution by an amount that increased with wake age. In addition, the point of maximum vorticity did not always coincide with the apparent center of the vortex. These issues were addressed by conditionally averaging the images according to a realignment of the velocity measurements based on the position of the vortex and by defining the center of the vortex to be the center of swirl. The variation in circumferential velocity along a radius anchored to the center of swirl was used to identify the peak vortex velocity, which in turn defined the size of the vortex core.

McAlister, K. W., Tung, C., Sharpe, D. L., Huang, S. and Hendley, E. M.

"PRELIMINARY STUDY OF A MODEL ROTOR IN DESCENT"

NASA/TM-2000-208785, AFDD/TR-99-A-001, November 2000, Aeroflightdynamics Directorate, US Army Aviation Research and Technology Activity, Ames Research Center, Moffett Field, CA

Within a program designed to develop experimental techniques for measuring the trajectory and structure of vortices trailing from the tips of rotor blades, the present preliminary study focuses on a method for quantifying the trajectory of the trailing vortex during descent flight conditions. This study also presents rotor loads and blade surface pressures for a range of tip-path plane angles and Mach numbers. Blade pressures near the leading edge and along the outer radius are compared with data obtained on the same model rotor, but in open jet facilities. A triangular procedure based on two directable laser-light sheets, each containing an embedded reference, proved effective in defining the spatial coordinates of the trailing vortex. When interrogating a cross section of the flow that contains several trailing vortices, the greatest clarity was found to result when the flow is uniformly seeded. Surface pressure responses during blade-vortex interactions appeared equally sensitive near the leading edge and along the outer portion of the blade, but diminished rapidly as the distance along the blade chord increased. The pressure response was virtually independent of whether the tip-path plane angle was obtained through shaft tilt or cyclic pitch. Although the shape and frequency of the pressure perturbations on the advancing blade during blade-vortex interaction are similar to those obtained in open-jet facilities, the angle of the tip-path plane may need to be lower than the range covered in this study.

McAllister, L. G.

"ACOUSTIC SOUNDER"

US Patent 3,675,191, July 1972.

A method of recording upper atmospheric characteristics which comprises transmitting in a generally upward direction recurrent pulses of acoustic energy at a selected frequency band of operation at a repetition interval longer than that required to receive back a reflected signal from a target, receiving the back-scattered energy on a facsimile recorder or other indicating mechanism which records the time and/or intensity and/or duration of the backscattered energy to permit upper atmospheric characteristics to be determined at airports or other localities where such information is of vital importance, the apparatus including a transmitter to radiate the pulses of acoustic energy and to receive the backscattered energy and to record from it the required data.

McCauley, G. J., Marcus, P. S., Savas, O. and Durston, D. A.

"COMPUTATIONAL ANALYSIS OF A PASSIVE WAKE ALLEVIATION SCHEME"

AIAA Paper No. 2006-2820, San Francisco, CA, June 2006

The vortex wake generated by a large aircraft induces sizeable vertical forces and rolling moments on trailing aircraft during an encounter. Recent studies of wake alleviation have focused on experimental observations of both active and passive techniques for accelerating the breakdown of the vortical structures in these wakes through vortex instabilities. A subset of these studies have concentrated on the addition of outboard triangular flaps for passively inciting Crow-like instabilities in the trailing vortices. Accompanying computational studies have been limited to qualitative analyses of the general wake features and vortex breakdown. To help bridge the quantitative gap between experimental and computational results, a spectral Navier-Stokes simulation was used to analyze the evolution of the vortical structures in the wake to calculate the forces and rolling moments induced on a trailing wing. Significant reductions in both downwash and rolling moment are clearly present in the numerical work; the magnitude and time scale of these reductions correlate well with recent experimental studies.

McConville, R. P.

"DOPPLER ACOUSTIC VORTEX SENSING SYSTEM"

FAA-RD-75-28, October 1978, Avco, Wilmington, MA

This is the final report on the Doppler Acoustic Vortex Sensing System, (DAVSS) program carried out by Avco Corporation's Systems Division for the U.S. Department of Transportation, Transportation Systems Center. The objective of the program was the design of an engineered DAVSS capable of real-time detection, tracking, recording, and graphic display of aircraft trailing vortices. Problems related to such vortices are currently under intensive study by the U.S. Department of Transportation for the Federal Aviation Administration. This report presents hardware and software design aspects of the

system. The design of the acoustic antennas and transducers is described. System control, computer hardware and software, and system/subsystem interfaces are discussed.

McConville, R. P.

"INSTALLATION AND TEST OF DOPPLER ACOUSTIC SENSOR"

FAA-RD-76-223, October 1977, Avco, Wilmington, MA

This report presents details of the installation of a Doppler acoustic vortex sensing system at JFK Runway 31R, the hardware and software improvements made since installation, vortex diagnostic and tracking data and analysis, and conclusions and recommendations.

McConville, R. P. and Pfeiffer, G.

"A DOPPLER ACOUSTIC VORTEX SENSING SYSTEM FOR AUTOMATIC REAL TIME TRACKING OF AIRCRAFT TRAILING VORTICES"

Third Workshop on Atmospheric Acoustic, York University, Toronto, Canada, June 1975

An automatic real time vortex tracking system using Doppler acoustic scattering techniques has recently been built and installed at the J. F. Kennedy International Airport. The system is capable of operating in either the pulsed or cw mode and in the monostatic backscatter or the bistatic forward scatter configuration. Acoustic signals in the band 3-6 KHz are transmitted from fan beam antennas. The vortex scattered signals with their characteristic Doppler spectra are received in any of four receiving antennas each consisting of 12 pencil beams. The scattered signals are Doppler processed to determine the angle and, in the case of pulsed signals, the range of the scattering center. The angle or range-angle estimates are automatically interpreted using the actual geometry of the antenna elements to form vortex altitude-displacement tracks.

McCormick, B. W.

"HYDRODYNAMICS TO OUTBOARD TO ROTORS TO WAKE TURBULENCE TO EXPERT WITNESS: THE EXPERIENCES OF AN AERONAUTICAL ENGINEER OVER 60 YEARS"

AIAA Paper 2013-2402, June 2013, San Diego, CA.

Many think of the aeronautical engineer as someone with narrow interests and expertise. Yet, most programs leading to a BS in Aerospace Engineering require a myriad of classes in diverse areas like solid and fluid mechanics, thermodynamics, mathematics, controls, and structural mechanics. Thus the 'aero' engineer can do more than simply design and analyze aircraft. To illustrate the foregoing, your author would like to take advantage of the opportunity afforded by this lecture. In a sense, this is a brief condensation of his professional career to date and license is taken to use first person in the paper. I hope the paper does not come across as 'blowing my own horn.' I just want to point out some

of the many different and interesting experiences that I have enjoyed during more than 60 years of teaching, industrial and consulting practice.

McCormick, B. W.

"A STUDY OF THE MINIMUM PRESSURE IN A TRAILING VORTEX SYSTEM"

Ph.D. Thesis, June 1954, Penn. State Univ., University Park, PA

Theoretical, experimental, and semi-empirical investigations of the minimum pressure in trailing vortex systems of elliptic, rectangular, and delta wings are presented. The magnitude of the minimum pressure coefficient in the trailing vortex system of a wing increases nearly linearly with the angle of attack of the wings. This magnitude is almost independent of aspect ratio for elliptic wings but for rectangular wings is slightly higher, the greater the aspect ratio, for a given angle of attack. At a given angle of attack the magnitude of the minimum pressure coefficient increases with increasing Reynolds number. The thickness of the tip-vortex core, or the thickness of the edge of the trailing vortex sheet is determined by the thickness of the boundary layer on the lower surface of the wing at the trailing edge of the tip and not by any considerations of induced drag and kinetic energy of the vortex sheet itself.

McCormick, B. W.

"AIRCRAFT WAKES: A SURVEY OF THE PROBLEM"

Symposium on Turbulence, Federal Aviation Administration, Washington, DC, March 1971

A large aircraft generates a vortex system which can present a hazard to lighter aircraft. The rollup, geometry, decay, and instabilities of trailing vortices are discussed. Their effect on other aircraft is considered and it is concluded based on a simplified analysis and accident records that relatively large aircraft can be susceptible to vortices from large jet transports. A brief history of the problem is included as well as an extensive bibliography covering the behavior of vortex systems and aircraft response.

McCormick, B. W.

"AN ASSESSMENT OF THE EFFECT OF A TRAILING VORTEX ON A FOLLOWING AIRCRAFT"

Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, Air Force Flight Dynamics Laboratory, AFFDL-TM-75-16-FGC, 1974, pp. 65-69

The various factors affecting the static rolling moment on an aircraft encountering wake turbulence are considered. The expressions for the total rolling moment are derived for a logarithmic velocity profile and for a Lamb or Rankine vortex.

McCormick, B. W.

"WAKE TURBULENCE"

Flight in an Adverse Environment, AGARD-LS-197, November 1994, pp. 1-1 - 1-15

Wake turbulence is a misnomer. Turbulence implies a random process whereas the term 'wake turbulence' refers to the hazard posed to smaller airplanes by the ordered, rotational flow in the trailing vortex systems behind larger airplanes. This lecture begins by examining the relationship of aircraft size, geometry, and operating conditions to the strength of an aircraft's trailing vortex system. Next, the velocity field initially induced close behind the generating airplane by its trailing vortex system is defined. This is followed by a discussion of the various ways in which a vortex system can dissipate and the many factors which affect the dissipation. In particular, the effects of atmospheric turbulence, ground proximity and vortex bursting on the ensuing behavior of the vortex system are considered. The paper continues with a study of the dynamics of an aircraft encountering the wake of a larger airplane. The degree to which an aircraft is threatened by a given vortex system of known characteristics is analyzed and the hazard posed by a given vortex system to a following aircraft quantified. Finally, the paper concludes with recommendations on possible ways to alleviate the safety and operational problems associated with wake turbulence.

McCormick, B. W. and Padakannaya, R.

"THE EFFECT OF A DROPPED WING TIP ON ITS TRAILING VORTEX SYSTEM"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 157-169

The effect of wing tip droop on the structure and position of its trailing vortex is studied. Spanwise load distributions determined by vortex lattice theory show that the stronger vortex moves from the tip of the wing to the hinge of the drooped tip as the droop angle increases. Experimental results on model wings are given which present the strength and the induced velocity profiles of the rolled-up vortex as a function of tip geometry. It is concluded that a droop angle approximately 90 degrees is optimum and results in a maximum induced velocity which is half of that produced by a plane wing.

McCormick, B. W. and Schumacher, W. J.

"AN INVESTIGATION OF THE TRAILING VORTEX SYSTEM GENERATED BY A JET FLAPPED WING OPERATED AT HIGH WING LIFT COEFFICIENTS"

AFFDL-TR-70-90, June 1970, Penn. State Univ., University Park, PA

The purpose of the investigation was to measure the geometry of the trailing vortex generated behind a jet flapped wing. Such vortices can pose a serious hazard to aircraft that penetrate them. Previous investigations performed on conventional wings indicate that these vortices persist for some time and have maximum tangential velocities which increase linearly with the lift coefficient. As future aircraft may employ high lift devices such as jet-flapped wings, the vortices generated could be even stronger. Two semispan models of a jet-flapped wing were tested in a subsonic wind tunnel.

Parameters varied during testing included the jet flap angle, angle of attack, aspect ratio and jet momentum coefficient. Vortex measurements were obtained using a vortex meter which measured the rotational speed of the fluid within the vortex. Values obtained were numerically integrated to yield the tangential velocity and circulation distributed through the vortex. Experimental results indicate that the maximum tangential velocity increases to a maximum and then decreases with continually increasing jet blowing. At high values of jet blowing, the vortex was found to decay rapidly downstream.

McCormick, B. W. and Surendraiah, M.

"A STUDY OF ROTOR BLADE-VORTEX INTERACTION"

26th Annual National Forum, American Helicopter Society, Washington, DC, June 1970

An experimental and analytical study of the rotor blade-vortex interaction problem was conducted. Time-dependent surface pressures were measured on a model rotor blade as it passed through a vortex generated by a fixed wing, mounted upstream of the rotor. The pressures were integrated to obtain the time-wise variation of the rotor section lift coefficients. The geometry of the test setup was varied to study the effect of such parameters as the distance of the vortex axis from the rotor plane, the angle at which the rotor blade intersects the vortex, the vortex size and strength, and the rotor rpm. Results of an approximate quasi-steady and unsteady two-dimensional analysis are compared with the measured section lift-coefficients.

McCormick, B. W., Tangler, J. L., and Sherrieb, H. E.

"STRUCTURE OF TRAILING VORTICES"

J. Aircraft, Vol. 5, No. 3, May-June 1968, pp. 260-267

A study of aircraft trailing vortex systems, involving actual flight testing as well as model testing and analytical considerations, has resulted in a method for predicting the vortex geometry and velocity field downstream of an aircraft. It is found that the vortex decay can be described by geometric similarity considerations and not by any modification of the Navier-Stokes equations. This conclusion is based on detailed velocity measurements made through the vortex immediately behind a test aircraft up to distances of approximately 1000 chord lengths downstream of the aircraft. This report includes a presentation of the data on which the conclusions are based, as well as a description of test equipment and procedures.

McCroskey, W. J.

"THE CHARACTERIZATION AND MODIFICATION OF WAKES FROM LIFTING VEHICLES IN FLUIDS"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. T-1 to T-10

The Fluid Dynamics Panel of AGARD arranged a Symposium on 'The Characterization and Modification of Wakes from Lifting Vehicles in Fluids' on 20-23 May 1996 in Trondheim, Norway. The purpose of the Symposium was '... to review and discuss recent developments in wake research for aircraft and the implications for air traffic regulations,' with a clear emphasis on the hazard of vortex encounters in civil aviation. Sessions were devoted specifically to operational procedures and aircraft spacings in airport terminal areas; to the aerodynamic interactions between trailing vortices and following aircraft; to trailing vortex structures, instabilities, atmospheric effects on wakes and vortex breakdown; and to miscellaneous issues, such as vortices generated by other vehicles and the interactions between vortex wakes and engine exhausts.

McCroskey, W. J.

"VORTEX WAKES OF ROTORCRAFT"

AIAA Paper 1995-0530, Reno, NV, Jan. 1995

This paper presents an overview of the complex unsteady vortical flows that comprise the wakes of rotary-wing aircraft; of the effects these tangled vortical structures have on the performance, noise, and vibration; and of some of the recent attempts to measure, predict, and control the phenomena. The main points are illustrated with several examples from the recent literature and technical conferences.

McCroskey, W. J. and Goorjian, P. M.

"INTERACTIONS OF AIRFOILS WITH GUSTS AND CONCENTRATED VORTICES IN UNSTEADY TRANSONIC FLOW"

AIAA Paper No. 1983-1691, Danvers, MA, July 1983

Unsteady interactions of concentrated vortices and distributed free-stream gusts with a stationary airfoil have been analyzed in two-dimensional transonic flow. A simple method of introducing such disturbances has been implemented numerically in the well-known transonic small-disturbance code LTRAN2, and calculations have been performed for two important classes of current aerodynamic problems. The first, which demonstrates many of the essential features of the interactions between helicopter rotor blades and their trailing-vortex wakes, is that of a discrete potential vortex convecting past an airfoil. The second is the response of a transonic airfoil to a transverse periodic gust, with and without the alleviation that can be achieved by the proper active control motion of a trailing-edge flap. In both cases, unsteady effects are found to play important roles in the shock-wave motion, in the overall flow-field development, and consequently, in the air loads on the airfoil.

McCutchen, C. W.

"INDUCED DRAG AND THE IDEAL WAKE OF A LIFTING WING"

J. Aircraft, Vol. 26, No. 5, May 1989, pp. 489-493

The wake of a lifting wing in inviscid flow is a pair of downward-sloping vortices with distributed vorticity in which the vortex lines are approximately helical. Within the vortices, fluid flows aft relative to fluid at infinity, and its Kelvin impulse more than nullifies the forward Kelvin impulse caused by the slope of the vortex pair. The momentum drag is therefore negative. Suction in the vortex cores more than counterbalances the negative momentum drag, and the difference between the two is the induced drag. The negative momentum drag is much smaller in magnitude than the drag due to suction except at high span loading. The induced drag is the integral over any transverse plane behind the wing of the difference between the energies of lateral and longitudinal motion per unit length. The drag contributed by the portion of the wing, or of any distribution of bodies, between any two transverse planes is equal to the growth of the above integral between the forward and after of these planes.

McCutcheon, G., McColgan, A. H., Hurst, D. and Grant, I.

"WAKE STUDIES OF A NACA 0015 WING USING PIV"

2nd World Engineering Congress, Sarawak, Malaysia, July 22-25, 2002

Detailed wake surveys were performed with an untwisted NACA 0015 airfoil section in a low-speed wind tunnel. The tests were conducted at a freestream velocity of 20/ms giving a Reynolds number of 200,000 based on the model wing chord. PIV was used to obtain cross-flow velocities at three downstream wake survey locations. At one wake position the effect of varying the angle of attack was investigated. Using a wake integration technique, lift and induced drag distributions were obtained along the model wing. Total lift and induced drag acting on the wing were then obtained using this flow field data.

McDonald, H., Ross, J., Driver, D. and Smith, S.

"WIND TUNNELS AND FLIGHT"

10th International Symposium on Applications of Laser Techniques in Fluid Mechanics, July 2000, Lisbon, Portugal.

The problem of extrapolating wind-tunnel data to flight conditions has been with us since the early days of aviation. The Wright brothers faced the problem, as has everyone else who used wind-tunnel data as part of their aircraft design process. The techniques used for correcting wind-tunnel data for wall and mounting effects are applied meticulously, but they are usually limited to linear flow approximations. The remaining issues for extrapolation are geometric differences between models and airplanes, non-linear effects of wind-tunnel walls and mounting systems, and the effects of Reynolds number. These effects are poorly understood or difficult to predict and they can result in a new aircraft falling short of its guaranteed performance. The current practice in wind-tunnel data corrections are

summarized and the missing physics identified. Current work on improving our understanding of the pertinent aerodynamics and to improve extrapolation methods are presented along with a discussion of further areas of inquiry.

McEwan, A. D. and Joubert, P. N.

"A SIMPLE MEANS OF MEASURING VORTEX STRENGTH, AND THE PERFORMANCE OF TRIANGULAR RAMP-TYPE VORTEX GENERATORS IN A UNIFORM VELOCITY FIELD"

Journal of the Royal Aeronautical Society, Vol. 66, December 1962, pp. 783-785.

The performance of triangular ramp vortex generators of a type used for boundary layer separation control, has been compared with that of equivalent wing or vane type of lifting generators, in a uniform velocity field, and was shown to be substantially inferior. Performance was established using a novel vortex strength measuring device of unusual simplicity, for which calibrations are given and applications are discussed.

McGinley, C. B. and Beeler, G. B.

"VORTEX UNWINDING IN A TURBULENT BOUNDARY LAYER"

J. Aircraft, Vol. 24, No. 3, March 1987, pp. 221-222

In this Note, the feasibility of vortex unwinding in a turbulent boundary layer has been demonstrated. While the true optimum unwinding configuration was not reached (i.e., the return to the nominally two-dimensional case), sufficient reduction in the isotach variation was achieved to verify the usefulness of this technique in turbulent boundary-layer vortex control. It is suggested that more detailed measurements of vortex strength and position will improve the optimization process and increase the amount of vortex unwinding. It should be noted that most of the applications suggested in this Note will benefit from vortex reduction as well as from complete vortex unwinding.

McGowan, W. A.

"AVOIDANCE OF AIRCRAFT TRAILING VORTEX HAZARDS"

AGARD, Flight Mechanics Panel, Baden-Baden, Germany, October 1970

Aircraft trailing vortex systems are made up of two counter-rotating cylindrical air masses, about a wing span apart, extending aft along the flight path. Vortex systems of large aircraft contain winds within and about these cylinders which can be hazardous to other aircraft encountering them in flight. Trailing vortices have been the cause of aircraft accidents. The greatest hazard potential exists in areas where aircraft of a wide range of classes are operating (e.g., utility/observation and heavy transport/bomber). Results of accident investigations, theoretical exercises, wind-tunnel experiments, and flight tests are used to describe the formation and severity of trailing vortices and the spatial extent of their influence, including factors governing persistence. This information is then used to

outline procedures for ready application by pilots, tower operators, and those concerned with the flow of traffic during tactical operations. Schemes under investigation to monitor remotely both the trailing vortex location and intensity in the airport area and to prohibit formation of high intensity vortices, through aircraft design, are discussed.

McGowan, W. A.

"NASA AIRCRAFT TRAILING VORTEX RESEARCH"

FAA Symposium on Turbulence, Federal Aviation Administration, Washington, DC, March 1971, p. 25

A brief description is given of NASA's comprehensive program to study the aircraft trailing vortex problem. Wind tunnel experiments are used to develop the detailed processes of wing tip vortex formation and explore different means to either prevent trailing vortices from forming or induce early break-up. Flight tests provide information on trailing vortex system behavior behind large transport aircraft, both near the ground, as in the vicinity of the airport, and at cruise/holding pattern altitudes. Results from some flight tests are used to show how pilots might avoid dangerous areas when flying in the vicinity of large transport aircraft. Other flight tests will be made to verify and evaluate trailing vortex elimination schemes developed in the model tests. Laser Doppler velocimeters being developed for use in the research program and to locate and measure vortex winds in the airport area are discussed. Field tests have shown that the laser Doppler velocimeter measurements compare well with those from cup anemometers.

McGowan, W. A.

"REMOTE DETECTION OF TURBULENCE IN CLEAR AIR"

AIAA/FAA Air Transportation and Society Conference, Key Biscayne, FL, June 1971

Various concepts for remote detection of turbulence in the clear air were reviewed. It was concluded that there is no technique now available for operational use to remotely detect and measure turbulence in the clear air. Several techniques are under both study and development which seem to have good potential for future application; namely, the laser Doppler radar for airborne and ground-based use, and ground-based ultrasensitive microwave Doppler radars. Terminal area turbulence-sensing-techniques, having considerable potential to assist with the aircraft wake problem, include the laser Doppler and acoustic radars. The acoustic radar seems like a simple approach currently. Further work is needed to see if the refinements in the system will result in a sophistication masking the original simplicity.

McGowan, W. A.

"AIRCRAFT WAKE TURBULENCE AVOIDANCE"

J. Aircraft, Vol. 9, No. 3, March 1972, pp. 197-198.

Aircraft trailing vortex systems are made up of two counter-rotating cylindrical air masses, about a wing span apart, extending aft along the flight path. Vortex systems of large aircraft contain winds which can be hazardous to other aircraft encountering them in flight. The greatest hazard potentials exist in areas where aircraft of a wide range of classes are operating (e.g., light utility/observation and heavy transport/bomber). Results of analytical studies and flight tests are used to describe the formation and severity of trailing vortices and the spatial extent of their influence. This information is then used to outline procedures for ready application by pilots, tower operators, and others concerned with the flow of traffic. The procedures provide the necessary appreciation of the physical attributes of trailing vortices, the potential hazards involved when encountering them, and how best to avoid the dangerous portions of the wake during flight operations.

McGowan, W. A.

"CALCULATED NORMAL LOAD FACTORS ON LIGHT AIRPLANES TRAVERSING THE TRAILING VORTICES OF HEAVY TRANSPORT AIRPLANES"

NASA TN D-829, May 1961, NASA Langley Research Center, Langley Station, VA

Results are presented of normal-load-factor calculations made for a light normal-category airplane and a light transport-category airplane traversing the trailing vortices generated by each of three heavy transport airplanes. With each light airplane, the normal load factors were determined for several penetration paths lying in a plane perpendicular to the trailing vortices and for three center-of-gravity locations and velocities. Also determined for the light normal-category airplane were the elevator deflection required to maintain 1 g flight and the vertical displacements of the airplane from the prescribed penetration paths while traversing the vortices. The results indicate that light airplanes traversing the wakes of currently operational heavy transport airplanes can experience loading conditions that exceed the design limit and, in some cases, the design ultimate load factors. For light airplanes traversing the wake generated by a proposed supersonic transport airplane the design ultimate load factors can be greatly exceeded. It was also shown that load factors imposed by the vortex system could be alleviated by elevator deflection; however, because of inherent pilot and control-system lag, the load factors would almost certainly be aggravated rather than alleviated.

McGowan, W. A.

"TRAILING VORTEX HAZARD"

SAE Paper No. 680220, Wichita, KS, April 1968

Light aircraft that encounter the trailing vortex system generated by heavy transport aircraft can experience high roll rates, loss of altitude, and large structural loads. Envelopes of vortex system velocities, duration and movement for various wind conditions have been determined. Specific operational procedures for the take-off, landing, and enroute phases of flight are suggested to enable the light aircraft pilot to avoid the wake turbulence of heavy aircraft.

McGowan, W. A.

"AIRCRAFT WAKE TURBULENCE AVOIDANCE"

12th Anglo-American Aeronautical Conference, Paper No. 72/6, Calgary, Canada, July 1971

Results of analytical studies and flight tests are used to describe the formation and severity of trailing vortices and the spatial extent of their influence. This information is then used to outline procedures for ready application by pilots, tower operator, and others concerned with the flow of traffic.

McGowan, W. A. and Charak, T.

"AIRCRAFT WAKE TURBULENCE"

16th Corporate Aircraft Safety Seminar, Flight Safety Foundation, April 1971, pp. 71-87

The physical characteristics of aircraft wake turbulence, or trailing vortices, are described: their formation, persistence, and whereabouts after being spawned by the wing lift. Analytical and flight test data are used to establish the inflight hazards associated with trailing vortex encounters. Techniques are suggested on how pilots can best avoid the damaging manifestations of aircraft wake turbulence for various flight regimes. The comprehensive aircraft wake turbulence research program supported by the NASA is outlined. Flight and model tests, and instrument development for remote wind sensing are used to better understand the aircraft wake turbulence generated by heavy transport aircraft. Concurrently, other studies are hopeful of uncovering ways to either prevent the trailing vortices from forming or induce early dissipation of dangerous winds.

McKenna, C. and Rockwell, D.

"TOPOLOGY OF VORTEX-WING INTERACTION"

Experiments in Fluids, Vol. 57, 2016, pp. 161-1 to 161-15.

A trailing vortex incident upon a wing can generate different modes of vortex-wing interaction. These modes, which may involve either enhancement or suppression of the vortex generated at the tip of the wing, are classified based on the present experiments together with computations at the Air Force Research Laboratory. Occurrence of a given mode of interaction is predominantly determined by the dimensionless location of the incident vortex relative to the tip of the wing and is relatively insensitive to the Reynolds number and dimensionless circulation of the incident vortex. The genesis of the basic interaction modes is clarified using streamline topology with associated critical points that show compatibility between complex streamline patterns in the vicinity of the tip of the wing. Whereas formation of an enhanced tip vortex involves a region of large upwash in conjunction with localized flow separation, complete suppression of the tip vortex is associated with a small-scale separation-reattachment bubble bounded by downwash at the wing tip.

McKenna, C., Fishman, G. and Rockwell, D.

"INTERACTION OF A TRAILING VORTEX WITH AN OSCILLATING WING"

Experiments in Fluids, Vol. 59, 2018, pp. 18-1 to 118-23.

A technique of particle image velocimetry is employed to characterize the flow structure of a trailing vortex incident upon the tip region of an oscillating wing (plate). The amplitude and velocity of the wing are nearly two orders of magnitude smaller than the wing chord and free stream velocity, respectively. Depending upon the outboard displacement of the incident vortex relative to the wing tip, distinctive patterns of upwash, downwash, and shed vorticity are observed. These patterns are a strong function of the phase of the wing motion during its oscillation cycle. At a given phase, the wing oscillation induces upwash that is reinforced by the upwash of the incident vortex, giving a maximum net upwash. Conversely, when these two origins of upwash counteract, rather than reinforce, one another during the oscillation cycle, the net upwash attains minimum value. Analogous interpretations hold for regions of maximum and minimum net downwash located outboard of the regions of upwash. The magnitude and scale of the vorticity shed from the tip of the wing are directly correlated with the net upwash, which takes different forms related to the outboard displacement of the incident vortex. As the location of the incident vortex is displaced towards the wing tip, both the maximum upwash and the maximum vorticity of the tip vortex initially increase and then decrease. For the limiting case where the incident vortex impinges directly upon the tip of the wing, there is no tip vortex or induced region of upwash. Furthermore, at small values of vortex displacement from the wing tip, the position of the incident vortex varies significantly from its nominal position during the oscillation cycle. All of the foregoing features are interpreted in conjunction with the flow topology in the form of streamlines and critical points, superposed on patterns of vorticity. It is shown that despite the small amplitude of the wing motion, the flow topology is fundamentally different at maximum positive and negative values of the velocity of the wing tip, that is, they are not symmetric.

McKenzie, R. L. and Reinath, M. S.

"THREE-DIMENSIONAL PLANAR DOPPLER VELOCITY MEASUREMENTS IN A FULL-SCALE ROTOR WAKE"

AIAA Journal, Vol. 43, No. 3, March 2005, pp. 489-499

The application of planar Doppler velocimetry (PDV) measurements to three-dimensional velocity vector fields in the tip-vortex flows between the blades of a full-scale UH-60 rotor operating in the 80-by 120-Foot Wind Tunnel at NASA Ames Research Center is described. The unique capabilities of PDV for remotely measuring complex velocity fields in large-scale flows are demonstrated and the factors affecting the quality of PDV data from a large-scale facility are defined. Because the wind tunnel is a non-circulating, in-draft configuration, and very large, the principal factor that prevented the acquisition of time-resolved, instantaneous measurements was the spatially and temporally sporadic behavior of the aerosol seeding in the sample area. Nevertheless, time-averaged velocity fields were obtained that characterize the locations and velocity distributions of the blade tip vortices and that provide magnitudes and directions of the velocity vectors in the surrounding flow with better than 1-cm spatial resolution within a square, 1.2 m x 1.2 m, sample area from distances up to 20 m.

McKillip Jr., R. M., Wachspress, D. A., Keller, J. D., Whitehouse, G. R., Quackenbush, T. R. and Boschitsch, A. H.

"DISTRIBUTED MULTI-VEHICLE SIMULATION INCLUDING HIGH-ORDER AIRWAKE REPRESENTATION"

60th Annual Forum, American Helicopter Society, June 2004, Baltimore, MD.

Attempts to simulate the dynamic interface (DI) environment of landing aircraft onto Navy ships typically incorporate extensive approximations in both the component aerodynamic models and their interaction. These lower fidelity models are employed to achieve real-time throughput speeds required in manned simulation, or may simply result from lack of data or sufficient analytical tools in the models themselves. A novel fully-coupled aerodynamic simulation that includes multiple aircraft simultaneously operating from a ship has been prototyped, and represents time-accurate couplings between aircraft wakes, ship superstructure, and ship air wake emanating from a moving platform. Various modeling simplifications for far wake decay and dissipation have been applied to this simulation and their effects evaluated to quantify the level of detail necessary to use this software as a DI testing predictive tool. Additional extensions to the model included the capability for full airframe wake modeling and an enhanced treatment of ship air wake effects. Favorable comparisons with a variety of datasets, and several simulation integration exercises, show the prototype model to be sufficiently general and robust to assure successful continued development to support a wide range of simulation applications.

McKissick, B. T., Rico-Cusi, F. J., Murdoch, J. L., Oseguera-Lohr, R., Stough III, H. P. and O'Connor, C. J.

"WAKE ENCOUNTER ANALYSIS FOR A CLOSELY SPACED PARALLEL RUNWAY PAIRED APPROACH SIMULATION"

AIAA Paper 2009-6943, September 2009, Hilton Head, SC.

A Monte Carlo simulation of simultaneous approaches performed by two transport category aircraft from the final approach fix to a pair of closely spaced parallel runways was conducted to explore the aft boundary of the safe zone in which separation assurance and wake avoidance are provided. The simulation included variations in runway centerline separation, initial longitudinal spacing of the aircraft, crosswind speed, and aircraft speed during the approach. The data from the simulation showed that most of the wake encounters occurred near or over the runway and the aft boundaries of the safe zones were identified for all simulation conditions.

McLean, D.

"WINGTIP DEVICES: WHAT THEY DO AND HOW THEY DO IT"

2005 Boeing Performance and Flight Operations Engineering Conference, Article 4, 2005.

In this paper we discuss the benefits of wingtip devices to the operator of an airplane and attempt to provide an accessible explanation of the physics underlying those benefits. We also discuss some of

the issues that affect design decisions and look at the level of benefit that has been achieved in one application, the API winglet on the 737NG.

McMahon, T. A.

"REVIEW OF THE VORTEX WAKE ROLL UP PROBLEM"

ASRL-TR-145-1, June 1967, Mass. Institute of Technology, Cambridge, MA

The near wake problem behind an airfoil is reviewed in the context of some eighteen references, both theoretical and experimental. It is found that the body of theoretical literature makes an inconsistent approximation about the axial component of velocity in the flow. The techniques of self-similar hydrodynamics, vortex system theory, and conservation of energy arguments as they apply to the roll-up problem are discussed. Some important experimental evidence seems to confirm that the near wake problem is basically three-dimensional and should be reexamined as such.

McMahon, T. A. and Widnall, S. E.

"VORTEX WAKE ROLL-UP AND VORTICITY CONCENTRATION BEHIND AN AIRFOIL"

ASRL TR 143-1, June 1967, Mass. Institute of Technology, Cambridge, MA

Some experimental evidence seems to confirm that the near wake problem is basically three-dimensional and should be reexamined as such. A concentration mechanism based on this three-dimensionality is proposed and found to predict a gradient of core circulation which is dimensionally correct and gives realistic answers when specific numerical cases are compared to published experiments. The correlation of experiment with theory involves a uniform translation of the theoretical points a specific distance upstream, implying that rotational fluid in the sheet requires a finite, uniform time to get to the core, no matter which downstream station is considered. A paradox in the role of viscosity in the concentrating mechanism is discussed.

McMillan, O. J., Schwind, R. G., Nielsen, J. N., and Dillenius, M. F. E.

"ROLLING MOMENTS IN A TRAILING VORTEX FLOWFIELD"

J. Aircraft, Vol. 15, No. 5, May 1978, pp. 280-286

Pressure distributions are presented which were measured on a wing near a tip vortex of known structure generated by a larger, upstream semispan wing. Overall loads calculated by integration of these pressures are checked by independent measurements made with an identical model mounted on a force balance. Several conventional methods of wing analysis are used to predict the loads on the following wing. Strip theory is shown to give uniformly poor results for loading distribution, although predictions of overall lift and rolling moment are sometimes acceptable. Good results are obtained for overall coefficients and loading distribution by using linearized pressures in vortex-lattice theory in

conjunction with a rectilinear vortex. The equivalent relation from reverse-flow theory that can be used to give economic predictions for overall loads is presented.

McMillan, R.

"MILLIMETER-WAVE RADIOMETER FOR DETECTING MICROBURSTS"

Fourth Combined Manufacturers' and Technologists' Conference, Part 2, NASA Langley Research Center, Airbourne Windshear Detection and Warning Systems, VA, September 1992, pp. 781-803

This paper describes a millimeter-wave radiometer for the detection of wind shear from airborne platforms or at airport terminals. This proposed instrument will operate near the group of atmospheric oxygen absorptions centered near 60 GHz, which it will use to sense temperature from a distance. The instrument will use two channels to provide two different temperature measurements, providing the basis for solution of two equations in two unknowns, which are range to the wind shear plume and its temperature. A third channel will measure ambient atmospheric temperature. Depending on the temperature difference between the wind-shear plume and ambient, the standard deviation of range measurement accuracy is expected to be about 1 km at 5 km range, while the temperature measurement standard deviation will be about one-fourth the temperature difference between plume and ambient at this range. The instrument is expected to perform usefully at ranges up to 10 km, giving adequate warning of the presence of wind shear even for high performance jet aircraft. Other atmospheric hazards which might be detected by this radiometer include aircraft wakes and vortices, clear-air turbulence, and wind rotors, although the latter two phenomena would be detected by an airborne version of the instrument. A separate radiometer channel will be provided in the proposed instrument to detect aircraft wakes and vortices based on perturbation of the spectrum of microscopic atmospheric temperature fluctuations caused by the passage of large aircraft.

McMillan, R. W.

"A HORIZONTAL ATMOSPHERIC TEMPERATURE SOUNDER: APPLICATIONS TO REMOTE SENSING OF ATMOSPHERIC HAZARDS"

International Journal of Infrared and Millimeter Waves, Vol. 14, No. 5, 1993, pp. 931-948.

Several atmospheric hazards, including wind shear, clear-air turbulence, and wake vortices cause special problems for aircraft. These phenomena are usually characterized by a change in temperature relative to ambient, which may be detected by a millimeter wave radiometer operating on an absorption line in the atmosphere. Because of available componentry with excellent performance and relative freedom from interference by water vapor, the family of oxygen absorptions centered near 60 GHz is considered the best atmospheric feature on which the design of such an instrument could be based. This paper describes a multi-channel radiometer operating near 60 GHz which should be capable of detecting the hazards mentioned above as well as other potential dangers such as the passage of strong fronts and other severe weather. It is shown that a carefully designed instrument will be capable of measuring range to a hazard to an accuracy of about 5 percent and temperature

difference to an accuracy of approximately half the actual measured difference, depending on range and temperature. An actual design is proposed, and graphs of expected performance are included.

McMinn, J. D.

"EXTENSION OF A KOLMOGOROV ATMOSPHERIC TURBULENCE MODEL FOR TIME-BASED SIMULATION IMPLEMENTATION"

AIAA Paper 1997-3532, August 1997, New Orleans, LA.

The development of any super/hypersonic aircraft requires the interaction of a wide variety of technical disciplines to maximize vehicle performance. For flight and engine control system design and development on this class of vehicle, realistic mathematical simulation models of atmospheric turbulence, including winds and the varying thermodynamic properties of the atmosphere, are needed. A model which has been tentatively selected by a government/industry group of flight and engine/inlet controls representatives working on the High-Speed Civil Transport is one based on the Kolmogorov spectrum function. This report compares the Dryden and Kolmogorov turbulence forms, and describes enhancements that add functionality to the selected Kolmogorov model. These added features are: an altitude variation of the eddy dissipation rate based on Dryden data, the mapping of the eddy dissipation rate database onto a regular latitude and longitude grid, a method to account for flight at large vehicle attitude angles, and a procedure for transitioning smoothly across turbulence segments.

McWilliams, I. G.

"HAZARD EXTENT ABOUT AIRCRAFT TRAILING WAKE VORTICES - ANALYTIC APPROACH"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 23-30

The proposed Vortex Advisory System makes use of the fact that under certain wind conditions, vortices cannot be detected within a protected corridor after 80 seconds. The width of the corridor is dependent upon the hazard extent about vortices. Two methods for estimating the hazard extent are presented: a static calculation of the rolling moment on a generic aircraft as a function of distance from the vortex axis; and a dynamic simulation of a B-720 encountering vortices at varying distances. Both methods were found to closely agree and yielded a value of 30 meters as a conservative estimate for the hazard extent about vortices.

McWilliams, J. C.

"THE EMERGENCE OF ISOLATED COHERENT VORTICES IN TURBULENT FLOW"

Journal of Fluid Mechanics, Vol. 146, 1984, pp. 21-43.

A study is made of some numerical calculations of two-dimensional and geostrophic turbulent flows. The primary result is that, under a broad range of circumstances, the flow structure has its vorticity

concentrated in a small fraction of the spatial domain, and those concentrations typically have lifetimes long compared with the characteristic time for nonlinear interactions in turbulent flow (i.e. an eddy turnaround time). When such vorticity concentrations occur, they tend to assume an axisymmetric shape and persist under passive advection by the large-scale flow, except for relatively rare encounters with other centers of concentration. These structures can arise from random initial conditions without vorticity concentration, evolving amid what has been traditionally characterized as the 'cascade' of isotropic, homogeneous, large-Reynolds-number turbulence: the systematic elongation of isolines of vorticity associated with the transfer of vorticity to smaller scales, eventually to dissipation scales, and the transfer of energy to larger scales. When the vorticity concentrations are a sufficiently dominant component of the total vorticity field, the cascade processes are suppressed. The demonstration of persistent vorticity concentrations on intermediate scales -- smaller than the scale of the peak of the energy spectrum and larger than the dissipation scales -- does not invalidate many of the traditional characterizations of two-dimensional and geostrophic turbulence, but I believe it shows them to be substantially incomplete with respect to a fundamental phenomenon in such flows.

McWilliams, J. C.

"THE VORTICES OF TWO-DIMENSIONAL TURBULENCE"

Journal of Fluid Mechanics, Vol. 219, 1990, pp. 361-385.

A solution of decaying two-dimensional turbulence at large Reynolds number is analyzed by means of an automated vortex census. The census identifies the flow structures which approximately conform to the idealized shape of an isolated, coherent vortex. It also determines vortex characteristics, such as amplitude, size, radial profile, and deformation from the ideal axisymmetric shape. The distributions of these characteristics within the vortex population are examined, as are their time evolutions. Interpretation of these distributions is made with reference to both the random initial conditions for the solution and the dynamical processes of vortex emergence, survival, and interaction.

Meacham, S. P., Flierl, G. R. and Send, U.

"VORTICES IN SHEAR"

Dynamics of Atmospheres and Oceans, Vol. 14, 1990, pp. 333-386.

The nature and stability of Kida's exact, time-dependent solutions for uniform, elliptical vortices in an ambient strain field are investigated. In addition to the classical Love mode of instability, we discover a class of resonant instabilities. Our linearized analysis is supplemented by numerical simulations of vortices in shear which follow the non-linear development of some of these instabilities.

Meadows, K., Kumar, A. and Hussaini, M.

"A COMPUTATIONAL STUDY ON THE INTERACTION BETWEEN A VORTEX AND A SHOCK WAVE"

AIAA Paper 1989-1043, April 1989, San Antonio, TX.

A computational study of two-dimensional shock vortex interaction is discussed in this paper. A second order upwind finite volume method is used to solve the Euler equation in conservation form. In this method, the shock wave is captured rather than fitted so that the cases where shock vortex interaction may cause secondary shocks can also be investigated. The effects of vortex strength on the computed flow and acoustic field generated by the interaction are qualitatively evaluated.

Meadows, K., Kumar, A. and Hussaini, M.

"COMPUTATIONAL STUDY ON THE INTERACTION BETWEEN A VORTEX AND A SHOCK WAVE"

AIAA Journal, Vol. 29, No. 4, February 1991, pp. 174-179.

A computational study of two-dimensional shock vortex interaction is discussed in this paper. A second-order upwind finite volume method is used to solve the Euler equations in conservation form. In this method, the shock wave is captured rather than fitted so that the cases where shock vortex interaction may cause secondary shocks can also be investigated. The effects of vortex strength on the computed flow and acoustic field generated by the interaction are qualitatively evaluated.

Meheut, M. and Bailly, D.

"DRAG PREDICTION AND WAKE SURVEY TECHNIQUES"

CEAS Katnet Conference on Key Aerodynamic Technologies, June 2005, Bremen, Germany.

This paper focuses on methods to calculate the drag components from flow field wake measurements. For many years, ONERA has developed an original method which aims at improving the understanding of local flow phenomena and wakes. The approach consists in writing the drag and the lift in terms of variables measured inside the wake to determine viscous, wave and lift-induced drag components. The first part of the paper is devoted to the theoretical formulations. The second part is dedicated to the wall influence on induced drag in wind tunnel. Direct Numerical Simulation is done to foresee these effects. In the last part, several examples are presented with subsonic and transonic tests. An original method allows the extraction of viscous and wave components from the profile drag to be carried out.

Meheut, M. and Bailly, D.

"DRAG-BREAKDOWN METHODS FROM WAKE MEASUREMENTS"

AIAA Journal, Vol. 46, No. 4, April 2008, pp. 847-862

This paper focuses on drag-extraction methods from flowfield wake surveys. For many years, ONERA has developed an original method which aims at improving the understanding of local flow phenomena. The approach consists in decomposing lift and drag into profile and induced components

from wake measurements. The definition of drag allows a phenomenological breakdown of the different drag sources, for which the physical interpretation requires an accurate description of the wake phenomena. It is the aim of this paper to closely analyze these drag sources and to establish an accurate breakdown. In the first section, the analytical definition of profile drag is reviewed. Several formulations commonly found in the literature are compared to determine their physical meaning and limits of applicability. From this analysis, a new drag-breakdown method is proposed and discussed. Computational fluid dynamics simulations are carried out to complete this study and to evaluate the accuracy of the new formulation. The latter is then applied to subsonic and transonic flows from wind-tunnel measurements.

Mehrle, A. H. and Gittler, P.

"COMPARISON OF ANALYTICAL AND NUMERICAL SOLUTION FOR OPTIMAL VORTEX DIFFUSER DESIGN"

PAMM, Vol. 5, Issue 1, 2005, pp. 471-472

This contribution deals with optimization of wing tip devices, so called vortex diffusers. A comparison is given between an analytical approach for obtaining the optimal circulation loading and the results of a numerical investigation using a lifting line method. The purpose of most wing tip devices is to reduce the induced drag of the main wing by converting vortex energy into thrust. To achieve an optimal design, a variational formulation originally proposed by Betz and Prandtl for air screws is applied to the circulation distribution of the diffuser blades. In extension to the inviscid formulation, a viscous correction is applied to account for frictional forces. To validate the analytical results, a comparison is given with numerical solutions from a lifting line method. The loading of the diffuser blades is parametrized and optimized with respect to resulting thrust by use of a quasi-Newton gradient method. Comparison shows that, knowing the velocity distribution in the near wake of the wing, considerable decrease of induced drag may be achieved making use of vortex diffusers. Although actual circulation loading may differ between the analytical and numerical estimation, resulting thrust agrees within a few percent.

Mehta, J. M.

"SELF-PRESERVATION OF TURBULENT WAKES"

J. Aircraft, Vol. 26, No. 1, January 1989, pp. 93-96

An experiment has been presented that describes wake flow development behind NASA GA(W)-1 airfoils. The measurements show that in the far wake, the mean velocity profiles demonstrate self-similar behavior irrespective of the nature of the upstream boundary layer. However, the processes by which different wakes reach the asymptotic state are much different for different types of wake generators.

Mehta, R. D. and Lim, T. T.

"FLOW VISUALIZATION STUDY OF A VORTEX-WING INTERACTION"

NASA TM-86656, November 1984, NASA Ames Research Center, Moffett Field, CA

A flow visualization study in water was completed on the interaction of a streamwise vortex with a laminar boundary layer on a two-dimensional wing. The vortex was generated at the tip of a finite wing at incidence, mounted perpendicular to the main wing, and having the same chord as the main wing. The Reynolds number based on the wing chord was about 5000. Two different visualization techniques were used. One involved the injection of two different colored dyes into the vortex and the boundary layer. The other technique utilized hydrogen bubbles as an indicator. The position of the vortex was varied in a direction normal to the wing. The angle of attack of the main wing was varied from -5 to +12.5 deg. The vortex induced noticeable cross flows in the wing boundary layer from a distance equivalent to 0.75 chords. When very close to the wing, the vortex entrained boundary layer fluid and caused a cross flow separation which resulted in a secondary vortex.

Meier, G. E. A.

"HELICOPTERS AND VORTICES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Helicopters and vortices have a special relation. Vortices are generating in an interaction with the rotor blades a major part of the noise of a helicopter. In a lot of research activities it was found, the interaction of the blade tip vortices with the following blade is generating the slap noise of helicopters heard in special directions. We focus our considerations in this paper on the mechanisms of noise generation by vortex blade encounters and on the observation and measurement techniques for locating the vortices in the wake of the rotor. The first part is therefore dealing with experiments and numerical calculations showing a two-dimensional vortex interaction with a two-dimensional airfoil section. The sound generation is clearly visible in the results and documents two different mechanisms of sound generation. The first one is a kind of bow shock which is radiated because the approaching vortex increases the incoming wind speed and the blade is producing a kind of bow shock this way. A second mechanism of generating steep sound waves is due to an increase of flow velocity on the surface of the airfoil. Here a supersonic flow pocket can be generated and the closing shock wave is radiated as a sound wave later when the vortex has passed the airfoil section. The rotor experiments with the flying helicopter have been made possible by a new optical technique, which is called BOS (Background Oriented Schlieren). This technique enables field recordings of density gradients in unlimited viewing fields. This way the interaction areas of a rotor flow field can be recorded. Results for two different helicopters have been achieved and show the generated vortices but also some spectacular vortex interactions.

Melander, M. V. and Hussain, F.

"POLARIZED VORTICITY DYNAMICS ON A VORTEX COLUMN"

Phys. Fluids A, Vol. 5, No. 8, August 1993, pp. 1992-2003.

It is shown that vortex core dynamics results from the interaction of two slowly deforming, but overlapping, helical vortex structures. These are the left- and right-handed components of the vortex, and are obtained by a generalized Helmholtz decomposition (the complex helical wave decomposition) of the vorticity field. This decomposition is based on a Fourier expansion in eigenfunctions of the curl operator, which has only real eigenvalues λ . The sum of eigenmodes with $\lambda > 0$ ($\lambda < 0$) constitutes the right (left) polarized component, and the vector lines of the field (e.g., vortex lines) are locally right (left) handed helices. It is found that for a localized vortex the polarized structures are also localized, a crucial result for physical space applications. The polarized vortex structures deform slowly (compared to unpolarized structures) and behave almost like solitary waves when isolated. It is shown that this is because the nonlinearity in the Navier-Stokes equations is largely suppressed between eigenmodes of the same polarity. Moreover, the helicity of polarized structures is very high. The interaction between overlapping polarized structures however gives each structure a different propagation velocity and results in some additional deformation. The latter is shown to occur mainly in two places: at the front of the structure where a low enstrophy bubble forms (which is a permanent feature in each of the polarized packets), and at the back where a tail develops. Otherwise, the deformation occurs on a much slower time scale compared to that for unpolarized vortices. Thus the rapid changes in the total vorticity field result from the superposition of two slowly deforming structures moving in opposite directions, as is the case for the one-dimensional (1-D) wave equation.

Melander, M. V., Zabusky, N. J. and McWilliams, J. C.

"SYMMETRIC VORTEX MERGER IN TWO DIMENSIONS: CAUSES AND CONDITIONS"

J. Fluid Mech., Vol. 195, October 1988, pp. 303-340.

Two like-signed vorticity regions can pair or merge into one vortex. This phenomenon occurs if the original two vortices are sufficiently close together, that is, if the distance between the vorticity centroids is smaller than a certain critical merger distance, which depends on the initial shape of the vortex distributions. The conclusions are based on an analytical/numerical study, which presents the first quantitative description of the cause and mechanism behind the restricted process of symmetric vortex merger.

Melber-Wilkending, S.

"AERODYNAMIC ANALYSIS OF JET-BLAST USING CFD CONSIDERING AS EXAMPLE A HANGAR AND AN AIRBUS A380 CONFIGURATION"

Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 92, 2006, pp. 152-159.

The paper describes the setup and validation of a process-chain based on the DLR-TAU code with adaptation and flow solver for the determination of the jet-wake behind jet engines for viscous flows is

shown. This jet-wake (often called jet-blast) plays an important role for the design and the operation of airports. As an example of the process-chain the jet-blast impact on a hangar by an Airbus A380 configuration is simulated using this technique.

Melber-Wilkending, S., Sturmer, A., Stumpf, E., Wild, J. and Rudnik, R.

"NUMERICAL HIGH LIFT RESEARCH II/III"

High Performance Computing in Science and Engineering '04, Springer, 2005, pp. 237-259.

The project NHLRes is concerned with the simulation of aircraft aerodynamics and thus belongs to the research field of computational fluid dynamics for aerospace applications. NHLRes comprises the numerical simulation of the viscous flow around transport aircraft high lift configurations based on the solution of the Reynolds-averaged Navier-Stokes equations. The project NHLRes consists of five parts representing the analysis of complex 3D-flow features, wake vortex simulation, optimization for three-dimensional high lift flow, aerodynamic interactions between the propeller and high lift wings and finally the usage of large eddy simulation of the flow around high lift configurations.

Meleshko, M., Konstantinov, Yu., Gurzhi, A. A. and Konovaljuk, T. P.

"ADVECTION OF A VORTEX PAIR ATMOSPHERE IN A VELOCITY FIELD OF POINT VORTICES"

Physics of Fluids A, Vol. 4, No. 12, December 1992, pp. 2779-2797.

Two-dimensional inviscid flows governed by a vortex pair in the presence of another point vortex or vortex pair on an unbounded plane are considered analytically and via numerical simulations. For some integrable cases of vortex motion, the stirring process of a fixed closed volume of surrounding fluid ('atmosphere') initially trapped by vortex pair is investigated. Using the full classification of vortex movement types, it is shown that for all cases of vortex pair direct and exchange scattering the stirring process is regular. Some internal atmosphere regions conserve their existence and form after vortex interaction, resulting a 'soliton like' behavior. For general cases of vortex pair mutual trapping, the stirring process is chaotic. For limiting cases of vortex motions, the fluid particles reveal a regular behavior. A simple model for the qualitative description of recent experiments on vortex dipoles interaction is discussed. Although clearly an extreme idealization, the model appears to shed some light on what to expect in laboratory experiments.

Meleshko, V. V. and Aref, H.

"A BIBLIOGRAPHY OF VORTEX DYNAMICS 1858-1956"

Advances in Applied Mechanics, Vol. 47, 2007, pp. 197-292.

The early papers in the new field of vortex dynamics were scattered among many journals in many countries and were written in a multitude of languages, primarily English, French, German, Italian and Russian. This diversity of publication venue and language, unfortunately, often makes the literature

rather difficult to identify and access for the modern researcher. About a century after Helmholtz's paper two major journals devoted to fluid mechanics would be started, *Journal of Fluid Mechanics* in 1956 and *Physics of Fluids* in 1957. After their initiation these journals attracted many of the major papers in vortex dynamics. Furthermore, the vast literature about vortex dynamics since the 1950's may be accessed through serial publications such as *Advances in Applied Mechanics* (published since 1948), *Progress in Aeronautical Sciences* (published since 1961), *Annual Review of Fluid Mechanics* (published since 1969), and several volumes devoted to 'Stromungsmechanik' of the extensive *Handbuch der Physik* (published since 1956). Other valuable sources are the proceedings of the International Congresses of Theoretical and Applied Mechanics (held every four years since 1924), along with other topical symposia, conferences, and workshops. There also exist many general treatises, surveys, textbooks, Ludwig Prandtl and (since 1957) Lanchester Memorial Lectures, etc. Hence, and this may be a somewhat optimistic assessment, the period that is most in need of a comprehensive bibliography is the century from 1858 to about 1956. It is such a bibliography that we have tried to provide in this paper.

Meleshko, V. V., Gourjii, A. A. and Krasnopol'skaya, T. S.

"VORTEX RINGS: HISTORY AND STATE-OF-THE-ART"

Journal of Mathematical Sciences, Vol. 173, No. 4, July 2011, pp. 1-37.

In the present paper, we describe the fascinating 150-year history of vortex dynamics, which started from the classical work by H. Helmholtz (1858). This work contains not only the general theorems on vortex motion, but also a special section devoted to axisymmetric circular vortex filaments and, in particular, to vortex rings. The aim of our investigation is both to clarify some purely mathematical questions connected with the Dyson model for coaxial vortex rings with a small circular cross-section in a perfect incompressible fluid to provide a historical overview of the achievements in experimental, analytical, and numerical studies of the interaction of vortex rings. The model is illustrated by several examples of the motion of vortex rings. Finally, we present a complete classification of the interactions of two coaxial vortex rings in a perfect fluid.

Meleshko, V. V., Gurzhi, A. A., Doernbrack, A., Gerz, T., Holzaepfel, F. and Hofbauer, T.

"INTERACTION OF TWO-DIMENSIONAL TRAILING VORTEX PAIR WITH A SHEAR LAYER"

International Applied Mechanics, Vol. 37, No. 7, 2001, pp. 948-957

The basic laws governing the interaction of a two-dimensional vortex pair with a shear layer of constant thickness are considered. The main idea of the study is to develop and adapt a simplified representation of a hydrodynamic flow based on a point-vortex model simulating the actual interaction of full-scale vortex patterns over the ground surface. It is shown that vortices with vorticity opposite in sign to the shear layer may stop or even ricochet from this layer, while the other vortex may penetrate through the layer. Numerical results are presented as plots and analyzed.

Melgosa, M., Prats, X., Ruiz, S., Tarrago, J., Busto, J. and Steen, M.

"A NOVEL FRAMEWORK TO ASSESS THE WAKE VORTEX HAZARDS RISK SUPPORTED BY AIRCRAFT IN EN-ROUTE OPERATIONS"

Seventh SESAR Innovation Days, November 2017, Belgrade, Serbia.

This paper presents the simulation environment developed within the framework of R-WAKE project, funded by SESAR 2020 Exploratory Research. This project aims to investigate the risks and hazards of potential wake vortex encounters in the en-route airspace, under current and futuristic operational scenarios, to support new separation standards aimed at increasing airspace capacity. The R-WAKE simulation environment integrates different components developed by different partners of the R-WAKE consortium, including simulators for weather, traffic, wake vortex phenomena, wake vortex interactions and different tools and methodologies for safety and risk assessment. A preliminary example is presented in this paper, in which 200 historical trajectories were simulated to show that the novel framework works properly. A WVE encounter has been detected in such first scenario, however with no significant safety effect on the follower aircraft. A second controlled scenario has been then run to force the detection of a severe wake encounter under realistic en-route conditions. Such scenario has given evidences that confirm the safety relevance of the underlying research concept.

Meloni, M.-T.

"THE CREDOS PROJECT: FINAL ACTIVITY REPORT"

DO-13, April 2010.

This document is the Publishable Final Activity Report of the Crosswind-Reduced Separations for Departure Operations (CREDOS) project. The CREDOS Project Website can be viewed at www.eurocontrol.int/credos.

Memon, M. O. and Altman, A.

"PIV INVESTIGATION INTO CROSS-STREAM BEHAVIOR IN WING WAKE FREE SHEAR LAYERS: CHALLENGES AND RESULTS"

AIAA Paper 2017-1461, January 2017, Grapevine, TX.

A fresh look at the cross-stream flow in the wake of a wing has revealed some surprising results and posed some experimental challenges. The wake behind a three-dimensional wing is formed through the interplay of different sources of drag. Lift induced drag is generated as a byproduct of downwash from wingtip vortices. Parasite drag results from form/pressure drag and a combination of the upper and lower surface boundary layers. These parasite effects amalgamate to create the free shear layer in the wake. Particle Image Velocimetry (PIV) experiments were performed in the cross-stream direction in the wake of an AR 6 wing with a Clark-Y airfoil in the UD Low Speed Wind Tunnel. The objective was to investigate flow topology of and around the wing wake free shear layer. Performing PIV in the cross-stream plane to capture and correctly resolve the entire wingtip vortex poses several challenges.

Resolving cross-stream flow in the free shear layer in the wake behind a wing is more challenging as the cross-stream flow is typically only small fraction of the freestream (out of plane) velocity. Reliable results can be systematically obtained by careful manipulation of test parameters, many beyond the range of existing commonly accepted heuristics. The resulting velocity components in and around the free shear layer in the wing wake showed counter flow in the cross-flow plane presumably corresponding to behavior associated with the flow over the upper and lower surfaces of the wing. An indication of the possibility of the transfer of momentum (from inboard to outboard of the wing) was identified through spanwise flow corresponding to the upper and lower surfaces through the free shear layer in the wake. A transition from minimal cross flow in the free shear layer to a well-established shear flow in the spanwise direction occurs in the vicinity of maximum lift-to-drag ratio (max L/D) angle of attack.

Memon, M. O. and Altman, A.

"WINGTIP VORTEX BEHAVIOR IN THE VICINITY OF THE MAXIMUM LIFT TO DRAG RATIO LIFT CONDITION"

AIAA Paper 2016-1847, January 2016, San Diego, CA.

Adverse effects of lift induced drag on the aerodynamic efficiency of aircraft are well known. Lift induced drag is generated as a byproduct of downwash from the wingtip vortices. The flow physics associated with wingtip vortex core axial flow transformation from wake-like (velocity less-than the freestream) to jet-like (velocity greater-than the freestream) behavior in the vicinity of the maximum lift to drag ratio (L/D) lift condition is explored. Particle Image Velocimetry (PIV) experiments were performed in the UD Low Speed Wind Tunnel in the near wake of an AR 6 wing with a Clark-Y airfoil to investigate the characteristics of the wingtip vortex at angles of attack ranging from 2 and 8 degrees. Results showed changes in the velocity distribution in the vortex inner and outer cores. Vorticity and energy distributions indicated the existence of the wake-like to jet-like transformation in the range of 4 to 6 degrees angle of attack. This range corresponds with the maximum L/D angle of attack of the Clark-Y tested. A relationship between the vortex core axial velocity profile changeover and the angle of attack at maximum L/D was identified. Improved understanding of this relationship could be extended not only to improve aircraft performance through the reduction of lift induced drag, but also to air vehicle performance in off-design cruise conditions.

Memon, M. O., Wabick, K., Altman, A. and Buffo, R. M.

"WINGTIP VORTICES FROM AN EXERGY-BASED PERSPECTIVE"

AIAA Paper 2014-0955, January 2014, National Harbor, MD.

The lens of exergy is used to investigate a wingtip vortex in the near wake over a range of angles of attack. Exergy is a concept commonly found in thermodynamically related disciplines in engineering; however, it has not been widely applied within the field of aerodynamics. In short, exergy is the measure of thermodynamically 'available' energy as determined through the more discriminating

second law of thermodynamics. The experiment in this paper was conducted in a circular water tunnel at the ILR Aachen. The data was taken three chord lengths downstream in the Trefftz plane of an aspect ratio (AR) 5 Clark-Y wing with a square edged wingtip using Particle Image Velocimetry (PIV). Intuitively, the minimum available energy state is expected to correspond to the maximum lift to drag ratio angle of attack. This, however, is not found to be the case in the present results. In general, points of inflection in the traditional lift and drag curves are identifiable in the wake by distinguishable changes in the exergy distribution across the wingtip vortex under the associated conditions. There are numerous additional surprises offered by looking at the wingtip vortex from the exergy perspective. Perhaps the most intriguing result is that although only 2-d Trefftz plane data was used to obtain the exergy distribution across the individual wingtip vortices, the crossover point for the out of plane change from wake-like to jet-like wingtip vortex core axial flow (indicating the peak lift to drag ratio) is identified by the in-plane exergy distribution. This crossover point is not identifiable in the evaluation of any other characteristics calculated from in-plane quantities. Consequently, the exergy method holds promise as a metric for the improvement of aircraft performance through the reduction of lift induced drag.

Memon, M. O., Wabick, K., Altman, A. and Buffo, R.M.

"WING TIP VORTICES FROM AN EXERGY-BASED PERSPECTIVE"

Journal of Aircraft, Vol. 52, No. 4, July-August 2015, pp. 1267-1276.

The lens of exergy is used to investigate a wingtip vortex in the near wake over a range of angles of attack. Exergy is the measure of thermodynamically 'available' energy as determined through the more discriminating second law of thermodynamics. Experiments were conducted in a water tunnel at Institute of Aerospace Systems at Aachen. The data were taken three chord lengths downstream in the Trefftz plane of an aspect ratio 5 Clark-Y wing with a square-edged wing tip using particle image velocimetry. Intuitively, the minimum available energy state is expected to correspond to the maximum lift-to-drag ratio angle of attack. This, however, is not the case here. Most interestingly, although only two-dimensional Trefftz plane data were used to obtain the exergy distribution across the individual wing-tip vortices, the crossover point for the out-of-plane change from wakelike to jetlike wing-tip vortex core axial flow (indicating the peak lift-to-drag ratio) is identified by the in-plane exergy distribution. This crossover point is not identifiable in the evaluation of any other characteristics calculated from in-plane quantities. Consequently, the exergy method holds promise as a metric for the improvement of aircraft performance through the reduction of lift-induced drag.

Mendenhall, M. R., Lesieutre, D. J. and Kelly, M. J.

"WAKE-INDUCED AERODYNAMICS ON A TRAILING AIRCRAFT"

Applied Aerodynamics Conference, Royal Aeronautical Society, July 2016, Bristol, UK.

NASA conducted flight tests to measure the exhaust products from alternative fuels using a DC-8 transport aircraft and a Falcon business jet. An independent analysis of the maximum vortex-induced

loads on the Falcon in the DC-8 wake was conducted for pre-flight safety analysis and to define safe trail distances for the flight tests. Static and dynamic vortex-induced aerodynamic loads on the Falcon were predicted at a matrix of locations aft of the DC-8 under flight-test conditions, and the maximum loads were compared with design limit loads to assess aircraft safety. Trajectory simulations for the Falcon during close encounters with the DC-8 wake were made to study the vortex-induced loads during traverses of the DC-8 primary trailing vortex. A parametric study of flight traverses through the trailing vortex was conducted to assess Falcon flight behavior and motion characteristics.

Mendenhall, M. R., Lesieutre, D. J. and Kelly, M. J.

"TRAILING VORTEX-INDUCED LOADS DURING CLOSE ENCOUNTERS IN CRUISE"

AIAA Paper 2015-3300, June 2015, Dallas, TX.

The trailing vortex induced aerodynamic loads on a Falcon 20G business jet flying in the wake of a DC-8 are predicted to provide a preflight estimate of safe trail distances during flight test measurements in the wake. Static and dynamic loads on the airframe flying in the near wake are shown at a matrix of locations, and the dynamic motion of the Falcon 20G during traverses of the DC-8 primary trailing vortex is simulated. Safe trailing distances for the test flights are determined, and optimum vortex traverse schemes are identified to moderate the motion of the trailing aircraft during close encounters with the vortex wake.

Meng, F., Schwarze, H., Vorpahl, F. and Strobel, M.

"A FREE WAKE VORTEX LATTICE MODEL FOR VERTICAL AXIS WIND TURBINES: MODELING, VERIFICATION AND VALIDATION"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012072-1 - 012072-8.

Since the 1970s several research activities had been carried out on developing aerodynamic models for Vertical Axis Wind Turbines (VAWTs). In order to design large VAWTs of MW scale, more accurate aerodynamic calculation is required to predict their aero-elastic behaviors. In this paper, a 3D free wake vortex lattice model for VAWTs is developed, verified and validated. Comparisons to the experimental results show that the 3D free wake vortex lattice model developed can make an accurate prediction of the general performance and the instantaneous aerodynamic forces on the blades. The comparison between momentum method and the vortex lattice model shows that free wake vortex models are needed for detailed loads calculations and for calculating highly loaded rotors.

Meng, H., Liu, Y. Q., Li, L. and Han, S.

"A NOVEL 3-D NEAR WAKE VORTEX MODEL FOR FAR WAKE SIMULATION"

2nd IET Renewable Power Generation Conference (RPG 2013), September 2013, Beijing, China.

Wake effect widely exists in wind farms, which causes output power loss and higher fatigue load. Consequently, wake simulation, especially far wake, is significant for the wind farm micro-siting and wind farm operation. Interestingly, the simulation of near wake, which governs the initial condition of far wake, cannot be avoided in far wake simulation. Due to the complicate flow characteristics of near wake region, some simple near wake processing methods have been proposed, which cannot effectively depict details in near wake region. Combined with the Prandtl's approximation for the tip-root loss factor, a vortex model is proposed in this paper to calculate the near wake flow field for far wake simulation. To improve the efficiency of this vortex method, Particle Swarm Optimization (PSO) algorithm is employed to optimize the parameters, the helix angle and vortex core radius of tip and root vortex. A good agreement with Prandtl's approximation is achieved, and the 3 directional components of velocity are predicted, which is more detailed than the near wake description of Jensen wake model.

Meng, J. C. S.

"THE PHYSICS OF VORTEX-RING EVOLUTION IN A STRATIFIED AND SHEARING ENVIRONMENT"

J. Fluid Mech., Vol. 84, Part 3, 1978, pp. 455-469

A semi-analytical numerical study was performed to simulate the development of a vortex ring in a stratified and/or shearing environment. Practical applications of the results of this study can be found in turbulence modelling and in studies of plumes and wakes. The objective is to follow exactly the evolution of a vortex ring so that the three-dimensional vortex-stretching mechanisms due to stratification and the shear effects, respectively, can be understood.

Meng, J. C. S. and Thomson, J. A. L.

"LASER DOPPLER VELOCIMETER SYSTEM SIMULATION FOR SENSING AIRCRAFT WAKE VORTICES, PART II: PROCESSING AND ANALYSIS OF LDV DATA"

PD-75-077, February 1975, Physical Dynamics Inc., Berkeley, CA.

A data analysis program has been constructed to assess the Scanning Laser Doppler Velocimeter system performance, to validate the simulation model, and to test various vortex location algorithms. The program takes either real or simulated Doppler spectra versus range and elevation, calculates the spatial distributions of various spectral moments (mean velocity, variance, skewness, kurtosis) or other spectral characteristics and presents these in a 3-D display. Each of the real or simulated scans can be processed by one of three different procedures: simple frequency or wavenumber filtering, matched filtering, and deconvolution filtering. Vortex tracks and system range resolutions are compared with theoretical predictions.

Meng, J. C. S. and Thomson, J. A. L.

"SIMULATION AND DATA ANALYSIS OF A SCANNING LASER DOPPLER VELOCIMETER SYSTEM FOR SENSING AIRCRAFT WAKE VORTICES"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 94-105

The objectives of this study are to simulate the response of a Scanning Laser Doppler Velocimeter System (SLDVS) in an aircraft wake environment and to display the expected spatial signatures. From analysis of these simulated signatures as well as flight data, optimal tactics for determining wake location and strength can be established.

Menkes, J. and Abernathy, F. H.

"AN ESTIMATE OF THE POWER REQUIRED TO ELIMINATE TRAILING VORTICES BY SUCTION"

P-514, May 1970, Institute for Defense Analyses, Arlington, VA

The use of suction devices in controlling the trailing vortex hazard for closely spaced parallel runways is examined. The feasibility of this proposal is examined by means of a computer simulation. It is established conclusively that the scheme has merit and that the power required to bring the hazard to acceptable levels is of the order of 2,000 hp per runway.

Menkes, J. and Abernathy, F. H.

"AN ESTIMATE OF THE POWER REQUIRED TO ELIMINATE TRAILING VORTICES BY SUCTION"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 575-576

A descending aircraft is affected by the interaction of its vortex system with the ground; if the ground effect could be modified, the vortex reaction would be affected. Such a modification is induced by suction. The conceptual scheme involves placing one or more ditches which house the suction blowers between the runways.

Menshov, I.

"TEARING INSTABILITY OF ISOLATED COMPRESSIBLE VORTICES"

Aeroacoustics, Vol. 13, No. 1, 2014, pp. 113-140.

The present paper addresses the instability of a compressible vortex flow. We consider a family of so-called isolated vortices -- the circular planar vortices that have zero circulation (net vorticity). The term 'isolation' implies the presence of a shield in the vorticity field -- a region of vorticity of common sign surrounding the central domain where the vorticity is oppositely signed. To model such a vorticity field, a generalized Taylor-type profile for the swirl velocity in the radial direction is employed, which involves two parameters: intensity I (proportional to the maximal velocity) and steepness S (characterizing the

scale of the shield zone). Vortices are assumed to be compressible and homentropic. The linear-stability analysis is carried out, which shows that isolated vortices can exhibit both stable and unstable behavior depending on the model parameters I and S . By numerical simulations of the non-linear stage, the unstable normal modes are shown to evolve towards tearing of the basic vortex with formation of smaller secondary vortical structures.

Men'shov, I. and Nakamura, Y.

"INSTABILITY OF ISOLATED COMPRESSIBLE ENTROPY-STRATIFIED VORTICES"

Physics of Fluids, Vol. 17, March 2005, pp. 034102-1-034102-15

The normal mode linear analysis is applied to investigate the stability of a circular isolated compressible vortex with the emphasis on studying the effect of entropy stratification of the basic flow on stability properties. We study a family of vortices that have zero total circulation, with the swirl velocity being presented by a Taylor-type distribution in the radial direction. The stratification of entropy is modeled by a Gaussian two-parametric profile whose parameters control the maximal of entropy is modeled by a Gaussian two-parametric profile whose parameters control the maximal deviation from the homentropic distribution and the extent of the entropic zone. Results presented concern the effect of these parameters and the vortex intensity on instability characteristics. In particular, in the case of homentropic flow, vortices considered are found to be stable only for sufficiently high intensities and cease to be stable as the intensity weakens. As an example of the situation where unstable normal modes can be excited, the scattering of sound waves by the vortex flow is considered. By simulating this process numerically, we show that the scattered field becomes unstable in the course of time and acquires a typical periodical pattern in polar angle. The characteristics of this instability (viz., the growth rate and the azimuthal phase frequency) coincide with those of the linear analysis very closely. This fact shows conclusively that the instability is caused by the induction of unstable normal modes in the vortex by means of sound irradiation.

Men'shov, I. and Nakamura, Y.

"ON INSTABILITY AND BREAKDOWN OF ISOLATED VORTICES"

AIAA Paper No. 2005-4674, Toronto, Canada, June 2005

The present paper addresses the instability and breakdown of a compressible vortex flow. We study a family of circular planar vortices that have zero total circulation, with the swirl velocity being presented by a generalized Taylor-type distribution in the radial direction. The vortex is assumed to be compressible and homentropic; its azimuthal velocity is characterized by two parameters: intensity that is proportional to the maximal velocity and 'steepness' that defines the typical scale of the opposite vorticity zone surrounding the core of the vortex. The linear analysis is conducted to investigate the evolution of normal mode disturbances imposed on the field of the basic flow. Results obtained concern the effect of the parameters and on instability characteristics. The far field analysis shows that the instability evolution in the linear stage is accompanied by radiation of monochromatic

sound waves with the frequency that equals the phase frequency of the unstable mode. Also included are results of the numerical simulation of the non-linear stage, which is related to the vortex breakdown. Initial disturbances of two types are considered that correspond to the eigenfunctions of $m = 2$ and $m = 3$ azimuthal numbers, respectively. The first evolves into a stable symmetrical rotating structure that contains two pairs of counter-rotating eddies and a central eddy. Oppositely, the evolution of the $m = 3$ mode is strictly unstable and results in complete distortion of the basic vortex.

Men'Shov, I. and Nakamura, Y.

"INSTABILITY MODES ACOUSTICALLY EXCITED IN BAROCLINIC VORTICES"

AIAA Paper No. 2002-2986, St. Louis, MO, June 2002

The normal mode linear analysis is applied to investigate stability of a circular compressible vortex with the emphasis of studying the baroclinic effect, i.e., the effect of entropy stratification of the basic flow on stability properties. The vortex to be studied has a Taylor-type velocity distribution. The stratification of entropy is modelled by a Gaussian two-parametric profile, whose parameters control the maximal deviation from the homentropic distribution and the extent of the entropic zone. The results presented concern the effect of these parameters and the vortex intensity as well on instability characteristics, as the growth rate and the azimuthal phase frequency. Particularly, the Taylor homentropic vortex is found to be stable for sufficiently high intensities only, and ceases to be stable as the vortex intensity weakens. It also presented an example situation, where unstable normal modes are excited. This is the scattering of sound waves by the vortex. By simulating this process numerically, we show that the scattered field due to incident of sound waves on the vortex becomes unstable, and takes a typical angular regular structure. The characteristics of this instability, i.e., the growth rate and the azimuthal phase frequency coincides with those of unstable normal modes very closely, which indicates the excitation of these normal modes in the sound scattering process.

Men'shov, I. and Nakamura, Y.

"A MECHANISM OF SOUND GENERATION FROM VORTEX PREDOMINANT FLOWS"

ICAS 2004 Paper 2004-3.4.1, August-September 2004, Yokohama, Japan.

The present paper addresses the vortex instability as a possible source mechanism of wake vortex sound. We study a family of circular planar vortices that have zero total circulation, with the swirl velocity being presented by a generalized Taylor-type distribution in the radial direction. The vortex is assumed to be compressible and homentropic; its azimuthal velocity is characterized by two parameters: intensity I that is proportional to the maximal velocity and 'steepness' S that defines the typical scale of the opposite vorticity zone surrounding the core of the vortex. The linear analysis is conducted to investigate the evolution of normal mode disturbances imposed on the field of the basic flow. Results obtained concern the effect of the parameters I and S on instability characteristics. The far field analysis shows that the instability evolution in the linear stage is accompanied by radiation of monochromatic sound waves with the frequency that equals the phase frequency of the unstable

mode. Also included are results of the numerical simulation of the non-linear stage, which is related to the vortex breakdown and subsequent sound emission.

Menzies, R. T. and Hardesty, R. M.

"COHERENT DOPPLER LIDAR FOR MEASUREMENTS OF WIND FIELDS"

Proceedings of the IEEE, Vol. 77, No. 3, March 1989, pp. 449-462.

The use of coherent Doppler lidar for remote measurements of atmospheric wind fields is receiving increasing consideration as a valuable tool for studies of atmospheric dynamics, both on a local scale using ground-based systems and on a global scale from an earth-orbiting satellite platform. The signal processing techniques for obtaining the velocity estimates, and the fundamental factors that influence coherent lidar performance in this context, are reviewed. The similarities and distinctions between Doppler lidar and Doppler radars are discussed. Coherent Doppler lidars now have the capability to map wind fields over selected regions in the lower atmosphere and greatly enhance the capability to visualize flow patterns in real time. Examples of this capability are presented. The concluding discussion concerns several of the salient features of the NASA concept for an earth-orbiting Doppler lidar to be launched in the late 1990s.

Mercan, B., Ostovan, Y., Dogan, E. and Uzol, O.

"EFFECT OF CHORDWISE MODULATED WAVEFORM TIP INJECTION ON THE CHARACTERISTICS OF THE TIP VORTEX"

AIAA Paper No. 2010-4270, June 2010, Chicago, Illinois.

This paper investigates the effect of chordwise modulated tip injection on the flow and turbulence characteristics of the tip vortex through experimental measurements downstream of a rectangular half-wing that has an aspect ratio of three. This injection technique involves spanwise jets at the tip that are issued from a series of holes along the chord line normal to the freestream flow direction. The injection mass flow rate from each hole is individually controlled using computer driven solenoid valves and therefore the flow injection geometrical pattern at the tip can be adjusted to any desired waveform shape, and can be steady or pulsed as well as moving or stationary waves along the chord. The measurements are performed in a blow-down wind tunnel using Constant Temperature Anemometry as well as Kiel probe traverses. Current data show consistent trends with previously observed effects of steady uniform tip injection such as the upward and outward motion of the vortex as well as increased levels of turbulence within the vortex core. The vortex size gets bigger with injection and the total pressure levels get reduced significantly near the vortex core. The injection pattern also seems to affect the size of the wing wake as well as the wake entrainment characteristics of the tip vortex. Depending on the injection waveform pattern the helicoidal shape of the tip vortex also seems to get affected.

Mercker, E. and Pengelo, K.

"FLOW VISUALIZATION OF HELICOPTER BLADE TIP VORTICES -- A QUANTITATIVE TECHNIQUE TO DETERMINE THE TRAJECTORY AND THE POSITION OF THE TIP VORTEX PATTERN OF A MODEL ROTOR"

18th European Rotorcraft Forum, Sept. 1992, Avignon, France.

A visualization has been conducted of the tip vortex pattern of a descending model helicopter rotor, using a system that employs a continuous single-laser light sheet, a triggerable fast-motion video camera, a powerful strobe-light, and an oil smoke generator. The laser light sheet can be cast in any desired cross-section perpendicular to the plane by means of a two-degree-of-freedom traverse system. A reference grid was placed in the plane of the light sheet after the rotor and airstream were stopped, to quantify the distance between a given blade and the corresponding tip vortices.

Merritt, G. E.

"WAKE GROWTH AND COLLAPSE IN STRATIFIED FLOW"

AIAA Journal, Vol. 12, No. 7, July 1974, pp. 940-949

The objective of this research was to obtain data that could be used to predict the effect of stratification on the development of a momentumless wake. Experiments were performed in which a grid was oscillated in a stably stratified flow to produce the steady-state counterpart of the momentumless wake of a self-propelled vehicle. A pH-sensitive indicator was used to produce a neutrally-buoyant tracer to visualize wake development and subsequent vertical collapse. Measured velocity profiles in the simulated wake indicated that it was nearly momentumless, and vertical temperature surveys revealed the degree of mixing in the wake. The wake growth before and after collapse and the distance to collapse were correlated by using power laws and a theoretical analysis of wake collapse. The scaling relations established for predicting stratified flow wake dimensions revealed that the important parameters were the Froude number, defined as the product of the flow velocity and the Brunt-Vaisala period divided by the initial wake size, and the ratio of the time after wake generation to the Brunt-Vaisala period. Using these parameters, two unique curves were obtained for estimating the horizontal width and vertical height of a wake in a stratified flow.

Merritt, G. E. and Russo, A. L.

"THE EFFECT OF INITIAL CONDITIONS ON STRATIFIED FLOW WAKE COLLAPSE"

AIAA Paper No. 1975-0118, Pasadena, CA, January 1975

The effect of initial conditions on wake growth and collapse in a stratified flow has been studied experimentally and analytically. A turbulence generator was in a flowing stream of thermally stratified water, and measurements were made with a laser Doppler velocimeter of turbulence intensity in the wake. The measured rate of turbulence intensity decay along the wake axis for different values of initial turbulence level was observed to agree well with an analysis based on the assumption that the turbulence is proportional to the measured rate of wake expansion in unstratified flow. Good agreement was noted between analytical predictions, based on a critical Richardson number from

atmospheric data limiting vertical growth and measurements of wake growth and collapse for different ambient stratifications (Froude numbers) and wake turbulence levels. The measurements revealed the considerable effect that the initial wake turbulence intensity has on subsequent wake development.

Mertaugh, L. J. and Damania, R. B.

"AN INVESTIGATION OF THE TRAILING VORTICITY BEHIND A STOL AIRCRAFT"

AFFDL-TR-73-138, December 1973, Mississippi State University, MS.

This report presents the results of a test program to measure the near-field wake behind the wing of a test aircraft, out of the ground effect. The test aircraft was a high-lift L-19 aircraft incorporating a distributed-suction boundary layer control system. The wake measurement probe was supported from the fuselage of the test aircraft and was mounted on a trolley which moved along a boom structure. The velocity measurements were made with a six-element hot-film anemometer. The near field wake data were obtained in two measurement planes located 0.64 and 5.10 feet behind the wing. Data were obtained at zero and full-flap deflection and true speeds of 46, 66, and 85 mph. The data are presented as contours of constant nondimensional longitudinal velocity increment within the measurement planes.

Mertaugh, L. J. and Devarayalu, K.

"FURTHER INVESTIGATIONS OF THE NEAR FIELD TRAILING VORTICITY BEHIND A STOL AIRCRAFT"

AASE-75-142, December 1975, Miss. State Univ., Mississippi State, MS

This report presents results of a test program to measure the velocity field in the near-wake behind the wing of a high-lift test aircraft. A direct measurement of the 3-component velocity vectors was made in several measurement planes located at various longitudinal positions behind the trailing edge of the aircraft wing. The test aircraft was a STOL L-19 equipped with a distributed suction boundary layer control system. Measurements were taken such that the velocity derivatives along all three coordinate axes could be computed. Thus, the three components of the vorticity vector could be determined at each point of the measurement matrix. It was found that, in general, velocity and vorticity vectors are not collateral. A design study was conducted to determine feasibility of a trailing probe support system which would allow detailed mapping of the wing wake velocity field at least 4 chord lengths behind the trailing edge of the generating wing. Such a system appears to be feasible and would provide a mechanism for further experimental study of the vortical flow at a point in the wake where roll-up is more developed.

Mertaugh, L. J., Damania, R. B. and Paillet, F. L.

"AN INVESTIGATION OF THE NEAR-FIELD WAKE BEHIND A FULL-SCALE TEST AIRCRAFT"

J. Aircraft, Vol. 14, No. 9, September 1977, pp. 894-902

Three-dimensional velocity field measurements were made on three transverse measurement planes located at 7.7, 33.3, and 61.2 inches behind the inboard-wing trailing edge of an aircraft in flight. The test aircraft as an L-19 modified to incorporate a distributed suction boundary-layer control system. Test data were obtained at various lift coefficients and with both zero and full flap deflections. Flowfield measurements were made with a total-vector hot-film probe mounted to a boom and traversing mechanism attached to the rear fuselage of the test aircraft.

Mertens, J.

"GLIDER MOTION IN THE VORTEX FIELD BEHIND A TOWING AIRCRAFT"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002.

One common method to start gliders is towing by aircraft. Experience by many pilots in towed gliders and experimental investigations provided strong influence of the vortex flow on the performance and the handling characteristics of the towed glider. Pupils or people not well trained in towing or not flying carefully can produce dangerous situations. Strong pitching motions may follow, and often strong lateral deviations by swinging from one side to the other cannot be avoided. In the past, the most dangerous situation was provoked by the glider climbing high over the towing aircraft. Now, with ultralight aircraft allowed for towing, the towing aircraft can fly so slow, that the glider stalls. The free flying glider has 6 degrees of freedom. This enables several oscillations. Here, the most interesting ones are: in longitudinal motion the (usually strongly damped) pitch oscillation and the phugoid; in lateral motion the dutch roll, usually weakly damped for gliders.

Metwally, O. M.

"THE INTERACTION OF A SUPERSONIC STREAMWISE VORTEX AND A NORMAL SHOCK WAVE"

PhD Thesis, August 1989, The Pennsylvania State University, University Park, PA.

A detailed experimental investigation on the generation of a turbulent, supersonic streamwise vortex and subsequent interactions with a normal shock wave are presented. The vortex is generated in the supersonic wind tunnel inviscid freestream of Mach 3 using a streamlined, axisymmetric strut-mounted swirl injector. Flow-angularity probe measurements show that the supersonic vortex core, having a streamwise Mach number of 3.0 and transonic tangential Mach numbers up to 0.9, resembles the incompressible vortex in its three-layered structure: an innermost viscous layer with solid body rotation, a logarithmic middle layer and an outer inviscid layer. Total temperature probe surveys show an isoenergetic vortical flow condition. The vortex is then passed through a normal shock (Mach disc) created by mismatching the static pressure of the vortical flow with that of the Mach 2 freestream. The resulting interaction, primarily observed by way of non-intrusive optical flow diagnostics, is shown to be sensitive to the initial swirl rate of the vortex. Passing a low-swirl vortex through the shock results in a weak interaction which resembles the inviscid, non-swirling flow case. For otherwise similar flow conditions, increasing the initial swirl rate of the vortex results in a strong, highly unsteady interaction as the shock distends upstream in a cone-like behavior and a recompression shock forms downstream.

Flow-angularity probe surveys show that the flow well downstream of both interactions is vortical again with a streamwise Mach number of 1.7. The study then covers two other Mach numbers of 2.2 and 3.5 for different initial swirl rates up to 0.4. Based on the current observations, a physical model that postulates the effect of the vortex breakdown phenomenon on the interaction flow pattern is presented. Navier-Stokes computations, utilizing the present initial flow conditions, partially support the physical model in predicting several key features of the observed strong interaction flow pattern.

Metwally, O. M. and Settles, G. S.

"MEASUREMENTS OF A SUPERSONIC TURBULENT VORTEX"

Proceedings 11th Symposium on Turbulence, October 1988, Rolla, Missouri.

Mean-flow measurements of a supersonic turbulent streamwise vortex are presented. This vortex was produced by the injection of a swirling flow along the centerline of a supersonic airstream at Mach 3. Directional Mach number distributions, obtained via a five-hole flow-angularity probe, reveal vortex characteristics like those of the incompressible case, even though rotational Mach numbers up to 0.8 were obtained. This work is the first step of a study of the supersonic vortex breakdown phenomenon.

Metwally, O., Settles, G. and Horstman, C.

"AN EXPERIMENTAL STUDY OF SHOCK WAVE/VORTEX INTERACTION"

AIAA Paper No. 1989-0082, January 1989, Reno, NV.

An experimental study of the interaction of a supersonic streamwise vortex with a normal shock wave is presented. The vortex is generated in a supersonic wind tunnel test section using a streamlined, axisymmetric strut-mounted swirl injector. The streamwise Mach number of the vortex has values of 2.2, 3.0 and 3.5, while the inviscid freestream flow in which the vortex is imbedded has a constant Mach number of 2.0. To create such an interaction, the vortex is passed through a Mach disk (normal shock) which results from mismatching the static pressures of the freestream and the vortex. The resulting interaction is observed to be highly unsteady. The Mach disk distends upstream, while a recompression shock forms downstream of the interaction. Five-hole pressure-probe and temperature measurements ahead of the interaction are used as initial conditions for an axisymmetric, Navier-Stokes computation. The computational results support the hypothesis that supersonic vortex breakdown constitutes a strong factor in the observed interaction flow pattern.

Meunier, P. and Hourigan, K.

"MIXING IN A VORTEX BREAKDOWN FLOW"

Journal of Fluid Mechanics, Vol. 731, 2013, pp. 195-222.

In this paper we present experimental and theoretical results on the mixing inside a cylinder with a rotating lid. The helical flow that is created by the rotation of the disc is well known to exhibit a vortex

breakdown bubble over a finite range of Reynolds numbers. The mixing properties of the flow are analyzed quantitatively by measuring the exponential decay of the variance as a function of time. This homogenization time is extremely sensitive to the asymmetries of the flow, which are introduced by tilting the rotating or the stationary disc and accurately measured using particle image velocimetry (PIV). In the absence of vortex breakdown, the homogenization time is strongly decreased (by a factor of 10) with only a moderate tilt angle of the rotating lid (of the order of 15 degrees). This phenomenon can be explained by the presence of small radial jets at the periphery which create a strong convective mixing. A simple model of exchange flow between the periphery and the bulk correctly predicts the scaling laws for the homogenization time. In the presence of vortex breakdown, the scalar is trapped inside the vortex breakdown bubble, and thus increases substantially the time needed for homogenization. Curiously, the tilt of the rotating lid has a weak effect on the mixing, but a small tilt of the stationary disc (of the order of 2 degrees) strongly decreases (by a factor of 10) the homogenization time. Even more surprising is that the homogenization time diverges when the size of the bubble vanishes. All of these features are recovered by applying the Melnikov theory to calculate the volume of the lobes that exit the bubble. It is the first time that this technique has been applied to a three-dimensional stationary flow with a non-axisymmetric perturbation and compared with experimental results, although it has been applied often to two-dimensional flows with a periodic perturbation.

Meunier, P. and Leweke, T.

"SECONDARY STRUCTURES IN A COROTATING VORTEX PAIR"

Journal of Visualization, Vol. 4, No. 2, 2001, p. 115.

This sequence shows the evolution of two perturbed corotating vortices, generated in water using impulsively moved flat plates. The Reynolds number based on the circulation of one vortex is approximately 3000. The vortex cores are visualized using red dye painted on the plate edges. In addition, a nylon thread coated with green fluorescent dye is placed in the middle between the two vortex centers. The corotating vortices, which in their basic state rotate around each other, are perturbed by adding a sinusoidal deformation to the edge of the vortex-generating plates. This creates a periodic perturbation of vorticity between the vortices, near the dyed thread, where the basic flow exhibits a hyperbolic stagnation point.

Meunier, P. and Leweke, T.

"UNSTABLE VORTEX MERGER"

Physics of Fluids, Vol. 12, No. 9, Sept. 2000, p. S6

We present visualizations of the merging of two initially laminar co-rotating vortices. The vortices are generated in water, at the edges of two flat plates impulsively started from rest, and visualized using fluorescent dyes.

Meunier, P. and Leweke, T.

"MERGING AND THREE-DIMENSIONAL INSTABILITY IN A COROTATING VORTEX PAIR"

Lecture Notes in Physics, Vol. 555, 2000, pp. 241-251

We investigate experimentally the interaction between two parallel laminar vortices of equal circulation. They are created by the impulsive displacement of two flat plates in a fluid initially at rest. The temporal evolution of the pair is analyzed with dye visualizations and quantitative measurements using Particle Image Velocimetry. For low Reynolds numbers, the vortices remain two-dimensional and merge into one. The size of the cores increases due to viscosity up to a certain limit, approximately a fourth of the separation distance, at which merging occurs. At higher Reynolds numbers, a three-dimensional instability is discovered, showing the characteristic features of an elliptic instability of the vortex cores. The two vortices still merge, but the final vortex is now turbulent.

Meunier, P. and Leweke, T.

"THREE-DIMENSIONAL INSTABILITY DURING VORTEX MERGING"

Physics of Fluids, Vol. 13, No. 10, October 2001, pp. 2747-2750

The interaction of two parallel vortices of equal circulation is observed experimentally. For low Reynolds numbers (Re), the vortices remain two dimensional and merge into one, when their time-dependent core size exceeds approximately 30% of the vortex separation distance. At higher Re , a three-dimensional (3-D) instability is discovered, showing the characteristics of an elliptic instability of the vortex cores. The instability rapidly generates small-scale turbulent motion, which initiates merging for smaller core sizes and produces a bigger final vortex than for laminar 2-D flow.

Meunier, P. and Villermaux, E.

"HOW VORTICES MIX"

J. Fluid Mech., Vol. 476, 2003, pp. 213-222

The advection of a passive scalar blob in the deformation field of an axisymmetric vortex is a simple mixing protocol for which the advection-diffusion problem is amenable to a near-exact description. The blob rolls up in a spiral which ultimately fades away in the diluting medium. The complete transient concentration field in the spiral is accessible from the Fourier equations in a properly chosen frame. The concentration histogram of the scalar wrapped in the spiral presents unexpected singular transient features and its long-time properties are discussed in connection with real mixtures.

Meunier, P., Ehrenstein, U., Leweke, T. and Rossi, M.

"A MERGING CRITERION FOR TWO-DIMENSIONAL CO-ROTAING VORTICES"

Physics of Fluids, Vol. 14, No. 8, August 2002, pp. 2757-2766

We propose a quantitative criterion for the merging of a pair of equal two-dimensional co-rotating vortices. A cross-validation between experimental and theoretical analyses is performed. Experimental vortices are generated by the roll-up of a vortex sheet originating from the identical and impulsive rotation of two plates. The phenomenon is then followed up in time until a rapid pairing transition occurs for which critical parameters are measured. In the theoretical approach, the nonlinear Euler solution representing a pair of equal vortices is computed for various nonuniform vorticity distributions. The stability analysis of such a configuration then provides critical values for the onset of merging. From this data set, a criterion depending on global impulse quantities is extracted for different shapes of the vorticity distribution. This theoretical statement agrees well with our experimentally based criterion.

Meunier, P., Le Dizès, S. and Lewke, T.

"PHYSICS OF VORTEX MERGING"

C. R. Physique, Vol. 6, 2005, pp. 431-450

This article deals with the interaction of co-rotating vortices, in configurations like those found in the extended near-wake of typical transport aircraft. The fundamental process of vortex merging is analyzed and modeled in detail in a two-dimensional context, giving insight into the conditions for merging and its physical origin, and yielding predictions for the resulting flow. Three-dimensional effects, in the form of an elliptic short-wave instability arising in the initial co-rotating vortex flow, are described and analyzed theoretically. They are found to cause significant changes in the merging process, such as earlier merging and larger final vortex cores. Illustrations from recent experimental, numerical, and theoretical studies are given, and the relevance of the results for applications to real aircraft wakes is discussed.

Meymaris, G., Sharman, R., Cornman, L. and Deierling, W.

"THE NCAR IN SITU TURBULENCE DETECTION ALGORITHM"

NCAR Technical Note, NCAR/TN-560+EDD, June 2019, Boulder, CO.

An In Situ Turbulence Detection Algorithm has been developed and implemented in a C code library for use by the aviation community (i.e., typically integrated into an onboard Aircraft Conditioning and Monitoring System (ACM) or other suitable onboard computer), and is described in detail in this report. Note that this In Situ EDR Algorithm described in the report uses vertical wind, and estimates a mean and peak EDR every minute and includes an event-based report triggering algorithm to lower the downlink costs without sacrificing too much data. While there are a few adjustable parameters that are weakly aircraft-dependent, the EDR output itself is developed to be aircraft-independent. An integrated quality control algorithm was designed to limit the amount of false turbulence detection while not impacting estimates of actual turbulence. The algorithm has been carefully tested against

simulations that indicate very good statistical performance. The algorithm is, at the time of writing, operating on about 1,400 aircraft worldwide, with many more expected.

Miake-Lye, R. C., Martinez-Sanchez, M., Brown, R. C. and Kolb, C. E.

"PLUME AND WAKE DYNAMICS, MIXING, AND CHEMISTRY BEHIND A HIGH SPEED CIVIL TRANSPORT AIRCRAFT"

J. Aircraft, Vol. 30, No. 4, July-August 1993, pp. 467-47.

The environmental perturbations caused by the exhaust of a high-speed civil transport (HSCT) depend on the deposition altitude and the amount and composition of the emissions. The chemical evolution and the mixing and vortical motion of the exhaust need to be analyzed to track the exhaust and its speciation as the emissions are mixed to atmospheric scales. Elements of an analytic model of the wake dynamical processes are being developed to account for the roll-up of the trailing vorticity, its breakup due to the Crow instability, and the subsequent evolution and motion of the reconnected vorticity. The concentrated vorticity is observed to wrap up the buoyant exhaust and suppress its continued mixing and dilution. The chemical kinetics of the important pollutant species will be followed throughout the plume and wake. Initial plume mixing and chemistry are calculated using an existing plume model, standard plume flowfield (SPF), with additional H/C/O, OH/SO₂, and NO_y chemistry and equilibrium H₂O condensation included. The species tracked include those that could be heterogeneously reactive on the surfaces of the condensed solid water (ice) particles when condensation occurs, and those capable of reacting with exhaust soot particle surfaces to form active contrail and/or cloud condensation nuclei.

Miake-Lye, R. C., Martinez-Sanchez, M., Brown, R. C. and Kolb, C. E.

"PLUME AND WAKE DYNAMICS, MIXING, AND CHEMISTRY BEHIND AN HSCT AIRCRAFT"

AIAA Paper No. 1991-3158, September 1991, Baltimore, MD.

The environmental perturbations caused by the exhaust of a high-speed civil transport (HSCT) depend on the deposition altitude and the amount and composition of the emissions. The chemical evolution and the mixing and vortical motion of the exhaust need to be analyzed to track the exhaust and its speciation as the emissions are mixed to atmospheric scales. Elements of an analytic model of the wake dynamical processes are being developed to account for the roll-up of the trailing vorticity, its breakup due to the Crow instability, and the subsequent evolution and motion of the reconnected vorticity. The concentrated vorticity is observed to wrap up the buoyant exhaust and suppress its continued mixing and dilution. The chemical kinetics of the important pollutant species will be followed throughout the plume and wake. Initial plume mixing and chemistry are calculated using an existing plume model, standard plume flowfield (SPF), with additional H/C/O, OH/SO₂, and NO, chemistry and equilibrium H₂O condensation included. The species tracked include those that could be heterogeneously reactive on the surfaces of the condensed solid water (ice) particles when condensation occurs, and those

capable of reacting with exhaust soot particle surfaces to form active contrail and/or cloud condensation nuclei (ccn).

Micallef, D., Akay, B., Ferreira, C. S., Sant, T. and van Bussel, G.

"THE ORIGINS OF A WIND TURBINE TIP VORTEX"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012074-1 - 012074-13.

The tip vortex of a wind turbine rotor blade originates because of a complex distribution of vorticity along the blade tip thickness. While the tip vortex evolution was extensively studied previously in other work, the mechanism of the initiation of the tip vorticity in a 3D rotating environment is still somewhat obscured due to lack of detailed experimental evidence. This paper therefore aims at providing an understanding of how tip vorticity is formed at the wind turbine blade tip and what happens just behind the tip trailing edge. Stereo Particle Image Velocimetry (SPIV) is used to measure the flow field at the tip of a 2m diameter, two-bladed rotor at the TU Delft Open Jet Facility (OJF). The rotor has a rectangular blade tip. Spanwise measurements were performed for both axial and yawed flow conditions with a very small azimuthal increment. A 3D, unsteady, potential flow panel method is also used for the purpose of better understanding the tip bound vorticity. A validation study is carried out with positive results. This paper is focused on axial flow results. A complex distribution of vorticity is found along the blade tip thickness. Just after release, the tip vortex becomes almost immediately round and well defined. Observations from the MEXICO rotor are confirmed again by a slight inboard convection of the tip vortex. This is explained by means of the effect of chordwise vorticity at the tip from the numerical solutions. The results presented in this work suggest that a more physical interpretation of the tip loss effect is required. Currently, inclusion of the tip effects is based primarily on either wake induced effects or on an empirical 3D correction for airfoil data. This research should stimulate a more rigorous approach, where the effects of the blade tip chordwise vorticity are implemented in tip correction models.

Michalke, A. and Timme, A.

"ON THE INVISCID INSTABILITY OF CERTAIN TWO-DIMENSIONAL VORTEX-TYPE FLOWS"

Journal of Fluid Mechanics, Vol. 29, Part 4, 1967, pp. 647-666.

As a contribution to the breakdown phenomenon of vortices in a two-dimensional free boundary layer, this paper deals with the question whether a single cylindrical (i.e. two-dimensional) vortex can become unstable. For this reason, a single vortex, as it occurs in a free boundary layer, is approximated by an axisymmetric vortex model. The inviscid stability theory of rotating fluids is then applied to this vortex model. By general stability criteria it was found that a vortex consisting of vorticity of one sign only is stable according to the Rayleigh criterion, but, if the vorticity has an extremum value outside the axis, may become unstable with respect to cylindrical disturbances. Furthermore, stability calculations

for three special types of vortices were performed. It was found that they were more unstable with respect to cylindrical disturbances than to three-dimensional ones.

Michanowsky, G.

"ULTRAVIOLET RECONNAISSANCE AS A REMOTE DETECTOR AND TRACKER OF WAKE TURBULENCE"

Final Report, November 1972, Amazonia Foundation Inc., New York, NY

An ultraviolet reconnaissance technique was tested as a potential remote detector and tracker of wing tip vortices. The technique uses the jet engine exhaust particulates and other atmospheric impurities as tracers of the vortices.

Michea, B., Desopper, A. and Costes, M.

"AERODYNAMIC ROTOR LOADS PREDICTION METHOD WITH FREE WAKE FOR LOW SPEED DESCENT FLIGHTS"

18th European Rotorcraft Forum, Sept. 1992, Avignon, France, pp. 27-1 to 27-12.

A numerical method was developed to simulate a helicopter rotor at low speed and for descent flights. It consists of the coupling between a 3D unsteady full potential code, FP3D, and a new code derived from a lifting line method with vortex elements for the wake with prescribed geometry, METAR. This new code, MESIR, has a free wake analysis to get the capability to compute Blade-Vortex Interactions. Furthermore, the parts of the wake interacting with the blade are isolated and included in FP3D through a lifting surface approach. The method is validated with flight test results from the SA349 Gazelle helicopter and wind tunnel tests for the US Army OLS rotor in the DNW wind tunnel.

Michel, U.

"HISTORY OF ACOUSTIC BEAMFORMING"

Berlin Beamforming Conference (BeBeC), November 2006, Berlin, Germany.

The development of the beamforming method (also called microphone antenna, phased array of microphones, acoustic telescope, or acoustic camera) is reviewed in this paper. The microphone antenna was invented by Billingsley (1974) and has since seen dramatic improvements due to the availability of better data acquisition and computing hardware. Recent mathematical and software developments invert the beamforming process and allow a quantitative determination of the sources. Beamforming is indispensable for the localization of sound sources on moving objects, on flying aircraft, on high-speed trains, on motor cars in motion, on open rotors like helicopter and wind turbine rotors. In these applications, the ability to follow the motion of the sources is important. The second important applications are source localization tests in the test sections of open and closed wind tunnels. The background noise suppression capability of the beamforming method is required here. The various applications are discussed with a long list of references.

Michel, U. and Bohning, P.

"INVESTIGATION OF AIRCRAFT WAKE VORTICES WITH PHASED MICROPHONE ARRAYS"

AIAA Paper No. 2002-2501, Breckenridge, CO, June 2002

Wake vortices of landing aircraft emit a faint noise that is audible when the wind speed is low. The noise might be related to aerodynamic parameters of the vortices. Results from a test of the suitability of phased microphone arrays for the investigation of wake vortices are presented. It is shown that it is possible to localize the two counter-rotating vortices in a horizontal scan plane and to determine their horizontal trajectories. It is also possible to estimate the frequency spectra of wake-vortex noise. The paper presents vortex-noise frequency spectra and sound source distributions of the wake vortices measured behind an Airbus A320, a Boeing 737, and a Boeing 757. The phased microphone array technique is shown to be an appropriate tool for wake vortex investigations. Recommendations for the design of suitable arrays of microphones are given.

Michel, U., Barsikow, B., Helbig, J., Hellmig, M. and Schuettpehl, M.

"FLYOVER NOISE MEASUREMENTS ON LANDING AIRCRAFT WITH A MICROPHONE ARRAY"

AIAA Paper 1998-2336, Toulouse, France, June 1998

The noise sources of landing commercial aircraft were examined with planar arrays consisting of 96 or 111 microphones mounted on an 8 m by 8 m plate under the glide path on the ground. It is shown that important airframe noise sources can be identified despite the presence of engine noise, i.e., landing-gear noise, flap side-edge noise, flap-gap noise, jet-flap interaction noise, slat-horn noise, slat-track noise. A surprising finding is a noise source near the wing tips of some aircraft which is tentatively called wake-vortex wing interaction noise. It is shown to be by far the strongest noise (6 dB(A) louder than the engines) on a regional jet aircraft.

Micheli, F. and Moller, T. J.

"LDV APPLICATIONS IN INDUSTRIAL SIZE WIND TUNNELS"

3rd ONERA-DLR Aerospace Symposium, June 2001, Paris, pp. S4-2/1-9.

LDV techniques are not widely used in large scale wind tunnel, although DLR and ONERA have great skill in those appliances. Some classical and recent aspects of LDV are briefly reminded, as well as some typical results. As was done in the LLF-DNW wind tunnel, partnership could lead to a more efficient use of the time, cutting by more than two the test duration. Working distances of 5m and synchronization with an helicopter rotor were not a problem due to available setup. Vortex fields were measured and qualified with respect to the blade location. One important problem is the ability to measure boundary layers in large wind tunnel. A test on a high lift wing configuration, also in LLF-DNW, is presented. The

model location measurements done during LDV acquisition allowed to compensate for the model movements and to accurately define the flow close to the airfoil. The common knowledge and tools of both partners are ready to be employed to get more turbulent data in such large wind tunnels.

Michelsen, J. A.

"MODELING OF LAMINAR INCOMPRESSIBLE ROTATING FLUID FLOW"

AFM 86-05, Sept. 1986, Dept. of Fluid Mechanics, Technical University of Denmark, Copenhagen, Denmark

A Finite Element Code for simulation of laminar incompressible flow has been established. The Navier Stokes equations are solved using primitive variables, i.e. velocities and pressure, the latter being eliminated via a penalty formulation. To study the special anatomies connected with rotating flow, for example vortex breakdown and Ekman layers, an axisymmetric frame of reference is considered. Computations have been carried out for a cylindrical vessel with rotating cover. The Reynolds number ranged from 0 to 2000. Comparison to measured data reveals excellent agreement. Fully developed pipe flow leaving a rotating pipe into a fixed pipe has also been studied. The vortex breakdown produced by this flow is handled without difficulties by the code. Results are in close agreement with earlier numerical solutions.

Mickle, R. E.

"INFLUENCE OF AIRCRAFT VORTICES ON SPRAY CLOUD BEHAVIOR"

Journal of the American Mosquito Control Association, Vol. 12, No. 2, 1996, pp. 372-379

For small droplet spraying, the spray cloud is initially entrained into the wingtip vortices so that the fate of the spray is controlled by the motion of these vortices. In close to 100 aerial sprays, the emitted spray cloud has been mapped using a scanning laser system that displays diffusion and transport of the spray cloud. Results detailing the concentrations within the spray cloud in space and time are given for sprays in parallel and crosswinds. Wind direction is seen to potentially alter the vortex motion and hence the fate of the spray cloud. In crosswind spraying, the vortex behavior associated with the 2 wings is found to differ, which leads to enhanced deposition from the upwind wing and enhanced drift from the downwind wing.

Migliore, P. G.

"ROTOR INDUCED FLOW FIELDS IN GROUND EFFECT IN THE VICINITY OF A VERTICAL STEP"

TR-12, January 1969, West Virginia University, Morgantown, WV

This analysis devises means of theoretically predicting the flow fields induced by hovering rotors in ground effect and influenced by the proximity of a vertical step. A two-dimensional investigation is

performed. Results appear to be qualitatively accurate within the confines of the wake cylinder and in areas very close to the wake boundaries.

Mikhailov, Y. S.

"EXPERIMENTAL SIMULATION OF THE IMPACT OF A VORTEX WAKE ON A GENERAL AVIATION AIRCRAFT MODEL IN THE TsAGI T-103 WIND TUNNEL"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 188-196

Investigations in the TsAGI T-103 wind tunnel has been an effective means of simulating the influence of the vortex wake behind a heavy aircraft during takeoff or landing on the aerodynamic characteristics of another aircraft moving along a trajectory close to the wake axis. Used for simulation was an airfoil lattice with spanwise differential deflections of its airfoil, which was mounted at the wind tunnel nozzle exit. The study into the flow structure and testing of a general aviation aircraft model have shown that the airfoil lattice creates in the test section flow angularity equivalent in terms of its effects to the vortex wake behind the Boeing 747 aircraft in landing configuration at a distance of 500m and more. [In Russian.]

Mikhailov, Y. S.

"VORTEX WAKE SIMULATION IN A WIND TUNNEL"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 197- 203

The setup modification was effectuated in TsAGI's T-103 wind tunnel to simulate in its test section a flow structure closely like that in the vortex wake behind a heavy aircraft. The original setup that included a cascade of two spanwise-sectioned, differentially deflectable wings was converted into a two-section tapered wing with the sections capable of differential deflection. The results are presented of studying the flow structure behind the modified setup which were obtained for two wing section setting angles (+10, -10, +6 and -6 degrees) and three values of freestream speed (50, 20 and 15 m/s).

Mikhailov, Y. S.

"ANALYSIS OF VORTEX WAKE EFFECT ON THE AIRCRAFT MODEL AND SEARCH FOR AERODYNAMIC MEANS TO COMPENSATE IT"

AIAA Paper No. 1998-5591, Anaheim, CA, September 1998

The vortex wake effect on the aerodynamic characteristics of a twin-engine general-aviation aircraft model has been studied in TsAGI's wind tunnel. The airfoil cascade with differentially deflectable sections along the span installed at the wind-tunnel nozzle exit was used to simulate the vortex wake impact. In addition to the landing configuration considered first, this work is devoted to the analysis of

the vortex wake effect on the aerodynamic characteristics of the model in cruise and takeoff configurations. Preliminary researches were carried out on the efficiency of some wing control surfaces to compensate for the vortex induced rolling moment. The results of numerical calculation of the vortex wake impact on the aircraft model in cruise configuration is also presented. The algorithm for computing aircraft aerodynamic characteristics has been modified to account for the vertical velocity component of the vortex wake.

Mikhailov, Y. S.

"ANALYSIS OF THE VORTEX WAKE EFFECT ON AIRCRAFT MODEL AERODYNAMIC CHARACTERISTICS"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 169-179

The vortex wake effect on the aerodynamic characteristics of a twin-engine general-aviation aircraft model with significant mid-section has been studied in TsAGI's T-103 wind tunnel. The airfoil lattice with differential deflection section along the span installed at the wind-tunnel nozzle exit was used to simulate the vortex wake. Tests were conducted with two airfoil lattice angular settings of ± 6 and ± 10 degrees which were equivalent of wake influence formed behind the Boeing 747 aircraft in landing configuration at distances away from it of 1500 and 500 m, respectively. In addition to the landing configuration considered earlier, this work analyzes the aerodynamic characteristics of the model in cruise and take-off configurations. The results are indicative of the model drag reduction when simulating the flight regime along the trajectory close to the axis of one of the vortices. Besides, there is a need for additional wing control surfaces to compensate a disturbing rolling moment. The study covers a wide range of angles of attack including the post-stall ones.

Mikhailov, Y. S. and Razdobarin, A. M.

"APPLICATION OF THIN LIFTING SURFACE METHODS TO COMPUTING EFFECTS OF A VORTEX WAKE ON AN AIRCRAFT"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 204-213

An analysis has been performed of the effectiveness of two computational aerodynamics methods developed through thin lifting surface theory in both linear and nonlinear formulations for computing vortex wake effects on aircraft aerodynamic characteristics. The problem of determining the aerodynamic characteristics of an encountering aircraft has been solved within the vortex-wake 'frozen' parameter approximation, ignoring influence of the aircraft on the vortex wake structure. Verification of these numerical methods against experimental data obtained in low-speed wind-tunnels, allows one to determine their application areas as well as to direct possible ways to their improvement.

Mikhailov, Y. S. and Razdobarin, A. M.

"NUMERICAL ESTIMATION OF THE VORTEX WAKE EFFECT ON AIRCRAFT AERODYNAMIC CHARACTERISTICS"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 192-197

The algorithm for computing aircraft aerodynamic characteristics has been modified with the use of the combined vortex lattice method thus allowing the account for the vertical velocity component of the vortex wake generated behind a heavy aircraft. The algorithm modification consisted in the correction of local sectional angles of attack for the downwash induced by the vortex wake. The comparison between the computed results and wind-tunnel experimental data has shown satisfactory agreement of main aerodynamic characteristics of the aircraft model in the wake behind the differentially set airfoil lattice. Computations determine accurately enough the region of changing the sign of the rolling moment as a function of angle of attack due to flow separation from one of the half-wings.

Mikkelsen, T.

"ON MEAN WIND AND TURBULENCE PROFILE MEASUREMENTS FROM GROUND-BASED WIND LIDARS: LIMITATIONS IN TIME AND SPACE RESOLUTION WITH CONTINUOUS WAVE AND PULSED LIDAR SYSTEMS - A REVIEW"

2009 European Wind Energy Conference, March 2009, Marseille, France.

Two principal different coherent laser Doppler wind lidar anemometers have recently become available on the wind energy market for ground-based vertical mean and turbulence measurements. These two types of laser Doppler based wind lidars are: continuous wave (cw) wind lidars and pulsed wind lidars. Although built on the same recent communication technology 1.55-micron telecom fiber technology, there nevertheless exists some fundamental differences between the lidars temporal and spatial resolution capabilities that impacts on their mean wind and turbulence measurements in the atmospheric boundary layer and therefore also of relevance for the wind energy assessment studies, and other existing wind and turbulence research applications. The two lidar types spatial and temporal resolution characteristics is here reviewed as described in the literature and their influence on mean and turbulence profiles as measured from ground-based lidar platforms probing the atmospheric surface layer will be discussed. An intercomparison of the sounding volume characteristics with two specific commercially available wind lidars, one of cw type and one of pulsed type, is presented together with best estimates of these specific lidar systems optical parameters. The two specific wind lidar systems considered here are: the cw wind lidar ZephIR available from National Power U.K., and the pulsed wind lidar named WindCube, Leosphere, Fr..

Mikkelsen, T.

"LIDAR-BASED RESEARCH AND INNOVATION AT DTU WIND ENERGY A REVIEW"

Journal of Physics, Conference Series, Vol. 524, 2014, pp. 012007-1 - 012007-16.

A brief account of the motivation leading to the development and testing of wind Lidars at DTU is given, followed by a summary of the ongoing investigations in the area of wind sensing and associated Lidar technologies. A new mobile research infrastructure WindScanner.dk has been developed, which measures wind and turbulence fields from sets of three simultaneously in space and time synchronized scanning lidars. One set consists of three fast scanning continuous-wave based wind lidars (short-range system), and another consisting of three synchronized pulsed wind lidar systems (long-range system). Since then, wind lidar profilers and WindScanners are routinely deployed and operated during field tests and measurement campaigns. Lidars have been installed and operated from ground, on offshore platforms, and also as scanning lidars integrated in operating turbines. As a result, wind profiles and also detailed 3D scanning of wind and turbulence fields have been achieved: 1) of the free wind aloft, 2) over complex terrain, 3) at coastal ranges with land-sea interfaces, 4) offshore, 5) in turbine inflow induction zone, and 6) of the complex and turbulent flowfields in the wakes inside wind parks.

Miklosovic, D. S.

"ANALYTIC AND EXPERIMENTAL INVESTIGATION OF DIHEDRAL CONFIGURATIONS OF THREE-WINGLET PLANFORMS"

J. Fluids Engineering, Vol. 130, July 2008, pp. 071103-1 - 071103-10

An analytic and experimental effort was undertaken to assess the effectiveness and efficiency of three winglets mounted chordwise to the tip of a rectangular wing. The winglets, with an aspect ratio of 4.6, were mounted on a half-span wing having an effective aspect ratio of 6.29. 13 configurations of varying dihedral arrangements were analyzed with a vortex lattice method and tested in a low-speed wind tunnel at a Reynolds number of 600,000. The analytic distributions of wake velocity, circulation, and downwash angle verified that highly nonplanar configurations tended to reduce and diffuse the regions of highest circulation and to create more moderate downwash angles in the wake. This was manifest as an overall drag reduction. More specifically, the results showed that the winglets could be placed in various optimum orientations to increase the lift coefficient as much as 65 percent at the same angle of attack, decrease the drag coefficient as much as 54 percent at the same lift coefficient, or improve the maximum L/D by up to 57 percent.

Miklosovic, D. S. and Bookey, P. M.

"AN ANALYTIC AND EXPERIMENTAL INVESTIGATION OF THE AERODYNAMIC PERFORMANCE ENHANCEMENTS OF MULTIPLE WINGLET CONFIGURATIONS"

2005 ASME Fluids Engineering Division Summer Meeting and Exhibition, FEDSM2005-77255, June 2005, Houston, TX

An experimental effort was undertaken to assess the effectiveness and efficiency of three winglets mounted chordwise to the tip of a rectangular wing (NACA 0018 section). The winglets, with an aspect ratio of 3.6, were mounted on a half-span wing having an aspect ratio of 3.1. Twenty configurations of varying dihedral arrangements were analyzed with a vortex lattice method and tested in a low-speed

wind tunnel at a Reynolds number of 600,000. In general, the arrangements involving high dihedral angles had lower performance increments, due to lower lift and higher interference drag. More specifically, the results showed that the winglets placed at 60, 45, and 30 degrees, respectively, produced nominal 4% higher lift and 46% lower drag. The most dramatic findings from this study show that positioning the winglet dihedral angles had the result of adjusting the point of maximum L/D and the magnitude of the pitching moment coefficient. These observations suggest that multiple winglet dihedral changes affect the lift, drag, and pitching moment in such a way that they are feasible for use as actively-controlled surfaces to improve the performance of aircraft at various flight conditions and to 'tune' the longitudinal stability characteristics of the wing.

Miksis, M. J.

"ON VORTICAL FLOW AND SOUND GENERATION"

SIAM Journal of Applied Mathematics, Vol. 50, No. 2, 2006, pp. 521-536.

The acoustic field induced by an unsteady vortical flow is analyzed. In particular, the limit where the reference length scale l of the vortical flow is much smaller than the reference length scale of the acoustic field is considered. At low Mach number M the leading-order solution of the vortical flow is an incompressible viscous flow. The far field behavior of the flow is matched to the five quadrupoles of the acoustic field and their strengths are related to linear combinations of second moments of vorticity. The compressibility effect of the vortical flow, of order M squared, induces an acoustic source which is of the same order as the quadrupoles. We also relate the strength of the acoustic source to the total dissipation energy of the incompressible vortical flow. Hence, if viscous effects are neglected, the acoustic source term will be absent. These results are applied to turbulent flows and their implications to the mean flow are discussed. The results are also employed to study the sound generated by the motion and decay of slender vortex filament(s).

Milanovic, I. M. and Kalkhoran, I. M.

"NEAR-WAKE MEASUREMENTS OF A DELTA WING IN A SUPERSONIC STREAM"

Journal of Aircraft, Vol. 38, No. 2, March-April 2001, pp. 315-325.

The near-wake region of a 75-deg sweptback delta wing was studied experimentally in a Mach 2.49 stream. Five-hole conical probe measurements were conducted vertically and horizontally through the primary vortices at the trailing edge and half-chord downstream of the planform for 7- and 12-deg angles of attack. The Mach number and pressure distribution profiles are summarized, and comparisons of flow properties at different survey stations are presented. A novel calibration approach using a three-dimensional Navier-Stokes solver to generate numerically the calibration data for a blunt-nosed five-hole conical probe over a range of Mach numbers and pitch angles was employed. The magnitude of the pitot, total, and static pressure deficits in the wake region increased with increasing angle of attack for the same measurement plane and decreased with the downstream distance. The swirl profiles have supersonic and high transonic peak magnitudes, and estimated core dimensions

suggest vortex stretching in the vertical direction and convection downstream. A decrease in the radial Mach number component confirms the vortex trajectory changes from a strong downward flow over the planform to a gradual return toward the freestream in the near wake. Unlike the experimental results from transonic and low-speed leading-edge vortices, the axial and total Mach number distributions in supersonic vortices are found to be wake like.

Miley, S. J.

"A CATALOG OF DEVICES APPLICABLE TO THE MEASUREMENT OF BOUNDARY LAYERS AND WAKES ON FLIGHT VEHICLES"

NASA CR-116776, January 1972, Mississippi State University, State College, Mississippi.

A literature search was conducted to assemble a catalog of devices and techniques which have possible application to boundary layer and wake measurements on flight vehicles. The indices used in the search were NACA, NASA, NASA STAR, IAS, USGRDR and Applied Science and Technology Index. The period covered was 1950 through 1970. The devices contained in the catalog were restricted to those that provided essentially direct measurement of velocities, pressures, and shear stresses. Pertinent material was included in the catalog if it contained either an adequate description of a device and associated performance data or a presentation of applicable information on a particular measurement theory and/or technique. When available, illustrations showing the configuration of the device and test condition data were also included.

Miller N. and Tang, J. C.

"THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE INSTANTANEOUS INDUCED VELOCITY FIELD IN THE WAKE OF A LIFTING ROTOR"

USAAVLABS TR-67-68, January 1968, Dynasciences Corp., Blue Bell, PA

Measurements have been made of the instantaneous and time-averaged values of the induced velocities in the wake of a full-scale helicopter in actual steady flight conditions. Simple, analytical methods are formulated to predict the instantaneous and time-averaged, induced velocities in the rotor wake. Calculated values of the induced velocities are compared with the experimental data, and agreement is obtained for the hovering flight condition.

Miller, A. B.

"ANALYTICAL STUDY OF CONDENSING TRAILING VORTEX BEHIND A PASSENGER AIRCRAFT AT SEA LEVEL"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 375-388

Within the framework of analytical approaches, a problem is solved on a condensing viscous vortex which simulates the trailing vortex behind the aircraft of the Boeing 747 type, flying at sea level. A parametric study was carried out of the condensation region and a simple formula for the 'dew surface', which bounds it, is obtained asymptotically. Along with the Eulerian description of the droplet fraction dynamics, the Lagrangian approach to the problem on droplet motion along the trajectories of air particles was used. Self-similar solutions of the problem are constructed within the Eulerian approach. Eventually, spatial relationships for optical scattering cross-sections of elementary flow volumes are obtained which are of interest in terms of aircraft wake vortex visualization.

Miller, A. P.

"AN ACCURATE METHOD OF MEASURING THE MOMENTS OF INERTIA OF AIRPLANES"

NACA Technical Note No. 351, October 1930, Langley Aeronautical Laboratory, Langley Field, VA.

This note contains a description of an improved apparatus and procedure used by the NACA for determining the moments of inertia of airplanes. The method used, based on the pendulum theory, is similar to that previously used, but a recent investigation of its accuracy has resulted in the improvements described herein. The error, when using the new apparatus and procedure, has been found to be of the order of 1 per cent.

Miller, E. A., Kadygrov, E. N. and Troitsky, A. V.

"FEATURES OF ATMOSPHERIC TEMPERATURE PROFILING IN POLAR REGIONS"

9th International Symposium on Tropospheric Profiling (ISTP), September 2012, University of L'Aquila, L'Aquila, Italy.

The most important part of the investigation of climate and meteorological conditions in Polar Regions is the monitoring of atmospheric boundary layer (ABL) parameters. Characteristic feature of the atmospheric boundary layer in polar latitudes is the presence of strong temperature inversions which are important for interactions with radiation cooling processes, advection of warm air and katabatic winds. In this connection the scientists of Central Aerological Observatory jointly with the specialists from the Radiophysical Research Institute in the end of the '90th years of the last century designed the remote method of measuring temperature profiles of ABL based on measurements of self-emitting heat radiation of atmosphere on frequency near 60 GHz. The evolution of the equipment based on experiences and results of temperature profiles measurements with the use of polar version of microwave profilers in 2000-2012 are presented in the report.

Miller, G. D. and Williamson, C. H. K.

"TURBULENT STRUCTURES IN THE TRAILING VORTEX WAKE OF A DELTA WING"

10th Turbulent Shear Flow Conference, August 1995, University Park, PA.

In the present study we investigate the near and far wake instabilities in the wake of a delta wing with a view to understanding the basic instabilities, mixing, and decay rate of the wake. Extensive visualization of the wake as a delta wing glides in free-flight through water reveals a 'braid wake' between the primary vortex pair and shows it imposing its structure on the primary pair. Hot wire measurements of the fluctuating velocity in the immediate near wake demonstrate the periodic shedding of the spanwise vortices in this 'braid wake' but also reveal a low-frequency oscillation nearer to the core of each primary vortex. The subsequent evolution of the wake is remarkable, as the scales of disturbances grow in what appear to be almost discrete steps, until a large-scale instability of the primary pair develops into a sequence of large-scale interconnecting vortex loops. Ultimately, the appearance is similar to a series of vortex rings. The streamwise wavelength of the ring-like structure was measured for these free-flight tests and for tests with the wing towed through water at a variety of speeds and angles of attack, yielding a wavelength between 4 and 5 spans (inter-vortex spacing of the primary pair). Further investigation is required before the relationship of these results to theoretical analyses can be ascertained. Experiments in which the incident velocity is perturbed at selected frequency and amplitude reveal that the wavelength of the final structure is reasonably insensitive to either parameter, unless the forcing becomes as large as 5% of free-stream velocity, also provided the forcing wavelength is far from the natural wavelength. While investigating the vertical mixing of the fluid due to the convecting vortices we found that the vertical extent of mixing is surprisingly large due to the formation of a 'curtain' of vortical fluid left above the descending vortex pair.

Miller, G. D. and Williamson, C. H. K.

"TURBULENT STRUCTURES IN THE TRAILING VORTEX WAKE OF A DELTA WING"

Experimental Thermal and Fluid Science, Vol. 14, 1997, pp. 2-8

In the present study, we investigate the near- and far-wake instabilities in the wake of a delta wing with a view to understanding the basic instabilities, mixing, and decay rate of the wake. Extensive visualization of the wake as a delta wing glides in free flight through water reveals a 'braid wake' between the primary vortex pair and shows it imposing its structure on the primary pair. Hot-wire measurements of the fluctuating velocity in the immediate near wake not only demonstrate the periodic shedding of the spanwise vortices in this 'braid wake' but also reveal a low-frequency oscillation nearer to the core of each primary vortex. The subsequent evolution of the wake is remarkable, as the scales of disturbances grow in what appear to be almost discrete steps, until a large-scale interconnecting vortex loops. Ultimately, the appearance is similar to a series of vortex rings. The streamwise wavelength of the ring-like structure was measured for these free-flight tests and for tests with the wing towed through water at a variety of speeds and angles of attack, yielding a wavelength between 4 and 5 spans (intervortex spacing of the primary pair). Further investigation is required before the relation of these results to theoretical analyses can be ascertained. Experiments in which the incident velocity is perturbed at selected wavelength and amplitude reveal that the wavelength of the final structure is reasonably insensitive to either parameter unless the forcing becomes as large as 5% of free-stream velocity, provided the forcing wavelength is far from the natural wavelength. While investigating the vertical mixing of the fluid due to the descending vortices, we found that the vertical

extent of mixing is surprisingly large owing to the formation of a 'curtain' of vortical fluid left above the descending vortex pair.

Miller, J. and Hallock, J.

"AIRCRAFT TAKEOFF CHARACTERISTICS"

DOT-VNTSC-FA127-PM-01-37, August 2001, Volpe Center, Cambridge, MA

The document investigates three essential characteristics of takeoff: rotation point, liftoff point, and takeoff angle. Distributions of the data are provided and analyzed. Trends in the data can be used to find the ideal location for wake vortex measuring equipment.

Miller, R. H.

"METHODS FOR ROTOR AERODYNAMIC AND DYNAMIC ANALYSIS"

Progress in Aerospace Sciences, Vol. 22, 1985, pp. 113-160.

The complex problems associated with the aerodynamics of blade/vortex interactions, the dynamics of a blade displaced out of its plane of rotation, and the position control of a hovering helicopter are discussed. Simplified models help to describe, and appear to be adequate for analyzing, many aspects of these problems. Free wake analyses are shown to be of importance in determining blade loads and performance for hovering flight or for wind turbines. Unsteady aerodynamics and careful definition of the wake formation are required when computing vibratory air loads in forward flight.

Miller, R. H.

"VORTEX THEORY FOR HOVERING ROTORS"

AIAA Journal, Vol. 20, December 1982, pp. 1754-1756.

The apparent paradox resulting from the application of classical propeller vortex theory to a hovering rotor is shown to be due to the neglect of wake contraction. When wake contraction is included, simple models may be developed which are able to accurately predict blade load distributions and wake geometries to a reasonable degree of accuracy.

Miller, T. S., Kliment, L. K. and Rokhsaz, K.

"DYNAMICS OF COROTATING VORTEX FILAMENTS PART 1: ANALYTICAL MODEL"

Journal of Aircraft, Vol. 43, No. 5, September-October 2006, pp. 1434-1439.

The interactions between two corotating vortex filaments of equal strength are investigated analytically. The Biot-Savart law is used to develop the equations of motion of the filaments, consistent

with Crow's formulation. Consistent with previous work, two modes of motion are defined and analyzed for stability. It is demonstrated that the mutual induction between the vortices leads to unstable motion of the filaments in the antisymmetric mode over a significant range of frequencies. Furthermore, the oscillatory motion of the filaments is proven to have a preferred direction.

Miller, T. S., Kliment, L. K. and Rokhsaz, K.

"ANALYTICAL INVESTIGATION OF CO-ROTATING VORTEX FILAMENTS WITH EXPERIMENTAL VERIFICATION"

AIAA Paper No. 2003-3601, Monterey, CA, May 2003.

The interactions between two co-rotating vortex filaments are investigated analytically. The Biot-Savart law is used to develop the equations of motion of the filaments, consistent with Crow's formulation. It is demonstrated that the mutual induction between the vortices leads to unstable motion of the filaments over a wide range of frequencies. Furthermore, the oscillatory motion of the filaments is proven to have a preferred direction. This behavior is demonstrated through comparison with experimental results obtained in a water tunnel.

Milluzzo III, J. I.

"CONTRIBUTIONS TOWARDS THE DETAILED UNDERSTANDING OF ROTOR FLOW FIELDS IN GROUND EFFECT OPERATIONS"

PhD Thesis, 2014, University of Maryland, College Park, MD.

High-speed flow visualization and high-resolution particle image velocimetry experiments were conducted on a two-bladed rotor that was operated in a hovering state, both out of ground effect (well away from the ground) and in ground effect at several rotor heights. Recent advances in flow diagnostic instrumentation allowed measurements of the rotor wake to be performed with unprecedented levels of resolution. In particular, the goal of the present work was to gain a better understanding of the fluid dynamics of the wake sheets (and the blade tip vortices) that were trailed from the blades. The present work examined the effects produced by two blade sets: 1. A baseline untwisted blade, 2. A twisted blade with -17 degrees of linear twist, and has revealed fluid dynamic details of the wake sheet that were hitherto unknown. For the measurements made with the rotor operating out of ground effect, the blade sets were tested at two blade loading coefficients of 0.053 and 0.08, although only the higher loading condition was tested with the rotors operating in ground effect. For the rotor operating out of ground effect, a helicoidal tip vortex was shown to form at the blade tip and the associated wake sheets were initially laid down as small-scale counterrotating vortical pairs. However, this initial vorticity quickly diffused and the sheet was then convected as concentrated bands of turbulence, including several dominant eddies. Several types of sheet dynamics were documented in the rotor wake, including sheet interactions with the tip vortices, the detailed behavior of this interaction depending on both the blade twist and the rotor thrust. At earlier wake ages, a sinusoidal wave-like perturbation was seen to be formed on the wake sheets, although the growth in

wave amplitude was limited as the sheets were convected and stretched in the velocity gradients in the downstream wake. When the rotor was operated in ground effect, the vorticity in the wake sheets persisted to much older wake ages. Wave-like perturbations did not form on the wake sheets when the rotors were operating in ground effect because the outward radial stretching of the rotor wake in the presence of the ground suppressed their development. The wake sheets were found to convect to the ground and introduce significant vorticity into the near-wall flow field closer to the rotor, contributing to fluctuations in the local flow velocities. The flow field near the ground was also observed to be significantly affected by the use of twist on the blade, with the wake impinging on the ground further inboard and closer to the rotor, which also resulted in higher flow velocities being produced further downstream.

Milluzzo III, J. I. and Leishman, J. G.

"VORTICAL SHEET BEHAVIOR IN THE WAKE OF A ROTOR IN GROUND EFFECT"

AIAA Journal, Vol. 55, No. 1, January 2017, pp. 24-35.

Particle image velocimetry measurements with high spatial resolution were conducted on a hovering two-bladed rotor system operating in ground effect above a planar surface. The objective was to gain a better understanding of the fluid dynamics of the wake sheets trailed behind rotating blades, with specific focus on their contribution to the development of the near-wall flowfield at the ground plane. Two blade sets were tested: 1) a baseline untwisted blade and 2) a twisted blade with 17 degrees of nose-down linear twist. Planar particle image velocimetry measurements were made for multiple regions of interest in the rotor wake to understand the temporal development of the wake sheets as they convected from their origin at the trailing edges of the blades until they interacted with the ground. The wake sheets were shown to contain relatively large amounts of concentrated vorticity, which persisted much longer in the wake than for the corresponding out of ground effect case. The wake sheet substantially influenced the nature of the developing flow over the ground, resulting in relatively large and higher transient excursions in the near-wall flow velocities further inboard and closer to the rotor. Performance measurements were also taken for both blade sets at various heights above the ground, with the untwisted blades showing the most significant increase in performance.

Milluzzo III, J. I. and Leishman, J. G.

"QUANTIFICATION OF THE EVOLUTION OF THE VORTICAL SHEETS IN THE WAKE OF A HOVERING ROTOR"

AIAA Paper 2014-3256, June 2014, Atlanta, GA.

High-resolution particle image velocimetry (PIV) measurements were conducted on a two-bladed rotor that was operated in the hovering state over a ground plane. Two blade sets were tested: 1. A baseline untwisted blade, 2. A twisted blade with about 17 degrees of linear twist. PIV measurements were made for multiple regions of interest in the rotor wake to understand the development and evolution of the wake sheets as a function of their age. Each blade set was tested at the same rotor

thrust and blade loading coefficient, both in and out of ground effect. The initial vorticity trailed into the wake sheets behind the blades was shown to be comprised of small pairs of counterrotating vortices of unequal strength. These wake sheets contained relatively large amounts of concentrated vorticity at early wake ages, with the rotor with the twisted blades having a somewhat stronger wake sheet overall. The concentrated vorticity quickly diffused into smaller scale eddies and turbulence as the sheets convected downstream in the rotor wake, but these structures were found to persist to relatively old wake ages and as far as the ground plane, which significantly affected the flow environment there.

Miloud, K. B., Dghim, M., Fellouah, H. and Ferchichi, M.

"EXPERIMENTAL INVESTIGATION ON THE EFFECT OF FREE STREAM TURBULENCE ON WINGTIP VORTICES"

AIAA Paper 2017-3037, June 2017, Denver, CO.

The interaction of a wingtip vortex with atmospheric Free Stream Turbulence (FST), a phenomenon that prevails in airport runways, may alter its trajectory and its strength downstream. This work is an experimental investigation on the effects of FST on the evolution and the wanderings of a wingtip vortex in the wake of a NACA0012 wing at an AOA of 5 deg. The measurements were conducted using a Stereoscopic PIV at a Reynolds number, Re , based on the chord of 200,000. FST intensities of 0.5 percent, 3 percent and 6 percent were selected. Measurements in the wake at $x/c=0.5, 2.5, 5$, and 7 show that the FST contributes to the vortex decay namely by decreasing the velocity deficit in the vortex core region. FST decreased circulation, increased the circumferential velocity peak decay and increased meandering amplitude.

Min, B.-Y. and Wake, B.

"MODIFIED HYBRID NAVIER-STOKES/FREE-WAKE METHOD FOR HOVERING ROTOR ANALYSIS"

Journal of Aircraft, Vol. 55, No. 1, January-February 2018, pp. 38-51.

The analysis of rotors in hover has always been a significant challenge. The presence of strong vortices underneath the rotor requires a large amount of grid points to properly capture the vorticity, and many time steps are required to reach a time-independent state. To bring the simulation cost to a more practical state for industry, a modified hybrid Navier-Stokes/free-wake method has been introduced, which successfully reduced grid count and simulation time by one order of magnitude compared to full Navier-Stokes simulations. In this hybrid method, Navier-Stokes and free-wake solvers are loosely coupled for fast convergence in hover. The S-76 model-scale blades with three tip designs were studied to assess current approaches. The proposed approaches showed reasonable-to-good correlation with measured figure of merit, thrust, and torque data. The effects of tip-design and tip-speed variations were captured well. The physical mechanisms of tip-design impact on hover performance were also studied.

Min, B.-Y., Reimann, C. A., Wake, B. E., Jee, S. and Baeder, J. D.

"HOVERING ROTOR SIMULATION USING OVERFLOW WITH IMPROVED TURBULENCE MODEL"

AIAA Paper 2018-1779, January 2018, Kissimmee, FL.

A transition model coupled with Spalart-Allmaras turbulence model has been recently developed and implemented to OVERFLOW solver. The Delayed Detached Eddy Simulation method in the OVERFLOW also has been modified with improved boundary layer shielding function and modified length scale definition. In this study, OVERFLOW with the improved turbulence model has been validated with simple 2D flat plate, SC-1095 airfoil, and S-809 airfoil. The validation showed good transition prediction and improved airfoil drag and stall angle prediction. Then, the model has been assessed for hovering rotor performance prediction. The selected rotor is the model scale S-76 rotor with swept-tapered tip. Fully turbulent simulation under-predicted the rotor Figure of Merit. Without known freestream turbulence intensity level, variation has been made from 0.5% to 2% intensity level to demonstrate the impact of transition to hover performance. The result showed performance increase significant enough to cover the error between measured data and fully turbulent simulation. The added DDES model slightly lowered the hover performance prediction with current grid.

Miranda, J. A.

"THE STRUCTURE OF A TRAILING VORTEX WAKE"

MS Thesis, May 1996, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Experiments have been performed in the spiral wake that surrounds the vortex shed from the tip of a rectangular NACA 0012 half wing. Both single-point and simultaneous two-point hot-wire measurements were made ten chord lengths downstream of the wing at a Reynolds number of 320,000. The structure of this flow consists of a small concentrated vortex core, surrounded by a circulating velocity field that winds the wake into a spiral about the core. Small amplitude wandering motions of the core were detected and quantitative estimates of the wandering amplitude and its contributions to the Reynolds stress fields were found. Outside of the core region the turbulence structure is dominated by this spiral wake. The maximum turbulence levels exist in the part of the wake that begins to spiral about the core. The 3-D region is the region where the wake is wound about the vortex and the 2-D region is the nearly two-dimensional portion of the wake inboard of the wing-tip. The stresses in the 3-D region, when scaled on local length and velocity scales, increase significantly over those in the 2-D region. This increase is presumably a consequence of the additional rates of strain imposed on the wake by the vortex. Stretching intensifies turbulent structures aligned with the stretching direction. Two-point measurements were made in the 2-D and 3-D regions of the wake to reveal the spanwise extent of the instantaneous turbulent structures in the wake. A high correlation was found at the smallest probe separations. There are stronger correlations and coherence in the 3-D region than in the 2-D region. Correlation length scales and coherence were found to increase significantly from the 2-D region to the peak turbulence region. This reveals that the stretching and additional rates of strain imposed on the wake by the vortex are organizing the spanwise turbulent structures.

Miranda, J. A. and Devenport, W. J.

"TURBULENCE STRUCTURE IN THE SPIRAL WAKE SHED BY A LIFTING WING"

AIAA Journal, Vol. 36, No. 4, April 1998, pp. 658-660

Velocity measurements have revealed in detail the structure of a spiral wake surrounding a wing-tip vortex. The tip vortex stretches, skews, and curves the wake. As the wake winds around the vortex, lateral stretching dramatically thins and weakens it, reducing the local wake half width and peak axial vortex deficit to about one third of their values in the two-dimensional region. The weakening of the wake influences turbulence stress profiles, all of which show much smaller stress levels in the tightly wound part of the spiral wake than in the two-dimensional region. The stretching also acts directly on the turbulence, producing significant anisotropy among the normal turbulence stresses. The damping effects of the stretching are to some small extent counteracted by skewing of the wake in the vortex tangential velocity field and under the action of its own embedded vorticity. The skewing gives rise to significant crossflow turbulence shear stress. Lateral curvature also plays a role, introducing asymmetry into the turbulence stress profile of the wake.

Miranda, J. A. and Devenport, W. J.

"TWO-POINT MEASUREMENTS IN TRAILING VORTICES"

AIAA Paper No. 1996-0804, Reno, NV, January 1996

Experiments have been performed in the spiral wake that surrounds the vortex core which is shed from the tip of a rectangular NACA 0012 half wing. The structure of this flow consists of a small concentrated vortex core, surrounded by a circulating velocity field that winds the wake into a spiral about the core. Small amplitude wandering motions of the core were detected. Quantitative estimates of the wandering amplitude and its contributions to the Reynolds stress fields were found. Outside of the core region the turbulence structure is dominated by this spiral wake. The maximum turbulence levels exist in the region of the wake that begins to spiral about the core. Two-point measurements were made in the 2-D and 3-D regions of the wake to reveal the spanwise extent of the instantaneous turbulent structures in the wake. A high correlation was found at the smallest probe separations. StroSreedharnger correlations and coherence in the 3-D region than in the 2-D region reveal that the three-dimensionality is organizing the spanwise turbulent structures.

Mirels, H. and Haefeli, R. C.

"THE CALCULATION OF SUPERSONIC DOWNWASH USING LINE VORTEX THEORY"

J. Aeronautical Sciences, Vol. 17, No. 1, January 1950, pp. 13-21

A straightforward procedure, based on lifting-line theory, is presented for obtaining the downwash behind lifting surfaces at supersonic speeds. The customary assumptions of an inviscid fluid and small

perturbation velocities are made. In particular, the vortex field associated with a supersonic lifting surface is examined; the vertical perturbation velocity field due to a line vortex segment of constant slope is presented in explicit form and is utilized to discuss some of the properties of line vortices in a supersonic free stream; and a bent lifting-line method and an unbent lifting-line method (horseshoe vortex system) are proposed for determining the downwash field behind swept and unswept wings, respectively. The lifting-line methods are applied to triangular and rectangular wings and give results that are in close agreement with the exact linearized solutions.

Mirels, H. and Haefeli, R. C.

"LINE-VORTEX THEORY FOR CALCULATION OF SUPERSONIC DOWNWASH"

NACA TN-1925, August 1949, NACA Lewis Flight Propulsion Lab., Cleveland, OH

The perturbation field induced by a line vortex in a supersonic stream and the downwash behind a supersonic lifting surface are examined for the purpose of establishing approximate methods for determining the downwash behind supersonic wings. Lifting-line methods are presented for calculating supersonic downwash. An unbent lifting line (horseshoe-vortex system) is used to compute the downwash behind rectangular and triangular wings and the results are compared with the exact linearized solutions. The chordwise position of the lifting line giving the best average agreement with the exact solution is noted for each wing. A bent lifting line is used to approximate the triangular wing, and the results are in good agreement with the exact solution except for points within 1/2 chord of the wing trailing edge. The use of a bent lifting line seems promising for obtaining accurate estimates of the downwash behind swept wings.

Mironer, A.

"ACCELERATED DIFFUSION OF WING TIP VORTICES BY HEATING"

AIAA Paper No. 1971-0616, Palo Alto, CA, 1971

This paper describes the effects of heating on the vorticity diffusion rate in a gas vortex. The heating causes an outward radial convection and an increased kinematic viscosity which greatly enhances the overall rate of vorticity diffusion from the core. The coupled heat conduction and fluid dynamical equations which describe the vortex heating process have been solved on a digital computer using a finite difference technique. For an initial temperature ratio between the outside induced region of the vortex and core of 2:1, the vorticity diffusion rate is very nearly twice as fast as in a vortex with no heating present.

Misaka, T. and Obayashi, S.

"LARGE EDDY SIMULATION OF WAKE VORTICES IN GROUND EFFECT WITH REALISTIC TERRAIN AROUND AIRPORT"

AIAA Paper 2017-4371, June 2017, Denver, CO.

We conducted large eddy simulation of wake vortices in ground effect with realistic terrain around an airport focusing on the airport specific behavior of wake vortices. We considered here a landing aircraft at Tokyo/Haneda Airport in Japan. We developed a framework for a distributed parallel computer that enables dynamic data management for load balancing and flow adaptive mesh refinement for wake vortex. The impact of a crosswind over airport buildings was only qualitatively evaluated so far by visualized images.

Misaka, T. and Obayashi, S.

"NUMERICAL STUDY ON JET-WAKE VORTEX INTERACTION OF AIRCRAFT CONFIGURATION"

Aerospace Science and Technology, Vol. 70, 2017, pp. 615-625.

The interaction of aircraft exhaust jet and wake vortex generated from a realistic aircraft configuration was numerically studied from the early phase until the complete roll-up. For numerical simulation we employed an unstructured mesh Reynolds-averaged Navier-Stokes (RANS) solver for the flow around an aircraft model, while a Cartesian mesh large-eddy simulation solver implemented on the framework of the building-cube method (BCM) was used for the simulation of the mid- to far-field wake. We especially investigated the feasibility of a coupling approach of the steady RANS solver and the Cartesian LES solver in the simulation of the jet-wake vortex interaction, where unsteady velocity fluctuations are stochastically reproduced based on RANS turbulence variables. The results showed that a multi-level Cartesian mesh of the BCM was effective to capture the evolution of aircraft wake including exhaust jet. The velocity profiles of a wake vortex are compared with several vortex models, which reveals that the velocity profiles fit with different vortex models depending on the vortex ages. The normalized temperature of exhaust jet is compared with the experiment, which confirms that the temperature information is appropriately transferred from the near- to far-field simulation.

Misaka, T., Holzaepfel, F. and Gerz, T.

"WAKE EVOLUTION OF HIGH-LIFT CONFIGURATION FROM ROLL-UP TO VORTEX DECAY"

AIAA Paper 2013-0362, January 2013, Grapevine, TX.

The development of aircraft's wake in high-lift configuration is studied from the roll-up until vortex decay. An aircraft model and the surrounding flow field obtained from high-fidelity Reynolds-averaged Navier-Stokes simulation are swept through a ground-fixed computational domain to initialize the wake. After the wake initialization, the large-eddy simulation (LES) of the vortical wake is performed until vortex decay. In this paper we consider an aircraft model in high-lift configuration where flaps and slats are deployed. In a few wingspan lengths downstream, the complex vorticity structures of the aircraft wake focus on co-rotating vortex pairs originated from wing- and flap-tips. The co-rotating vortex pairs merge at $t\text{-star} = 0.25$ and a common counter-rotating vortex pair is formed at around $t\text{-star} = 1.0$ entraining the turbulent aircraft wake into the vortex system. The rolled-up vortex features axial velocity in the vortex core with a magnitude of a half of the maximum tangential velocity.

Behavior of the formed vortex pair is like that of a vortex pair defined by a vortex model such as the Lamb-Oseen model. The initial descent speed of the vortices is slightly faster than that of the reference descent speed, i.e., $w = 1.1 w_{\text{zero}}$. In addition, it is confirmed that the ambient turbulence accelerates vortex linking and decay as in the case of a coherent vortex pair. The overall behavior of wake vortices is not affected by the different mesh resolutions considered here, except for vortex core radius.

Misaka, T., Holzaepfel, F. and Gerz, T.

"LARGE-EDDY SIMULATION OF AIRCRAFT WAKE EVOLUTION FROM ROLL-UP UNTIL VORTEX DECAY"

AIAA Journal, Vol. 53, No. 9, September 2015, pp. 2646-2670.

The evolution of aircraft wake vortices from the roll-up until vortex decay is studied by large-eddy simulation. An aircraft model and the surrounding flow field obtained from high-fidelity Reynolds-averaged Navier-Stokes simulations are swept through a ground-fixed computational domain to initialize the wake. After the wake initialization a large-eddy simulation of the vortical wake is performed until vortex decay. In this paper the methodology is tested with a NACA 0012 wing and applied to the DLR-F6 wing-body model in cruise condition and a long-range aircraft model in high-lift configuration which was used in the European Aircraft Wing with Advanced Technology Operation project. The correlation between the detailed roll-up process of the vorticity sheet shedding from the main wing and the characteristics of the rolled-up vortex pair such as vortex circulation, core radius, and separation is investigated with and without ambient turbulence. In both the DLR-F6 wing-body and the long-range aircraft models, the behavior of the formed vortex pair appears similar to that of a vortex pair defined by an analytical vortex model including the impact of ambient turbulence on vortex linking and decay. The velocity profile of a fully rolled-up vortex pair at around $t^* = 1.0$ agrees well with the Rosenhead-Burnham-Hallock vortex model.

Misaka, T., Holzaepfel, F. and Gerz, T.

"WAKE EVOLUTION OF WING-BODY CONFIGURATION FROM ROLL-UP TO VORTEX DECAY"

AIAA Paper No. 2012-0428, January 2012, Nashville, Tennessee.

The development of aircraft's wake vortex from the roll-up until vortex decay is studied. An aircraft model and the surrounding flow field obtained from high-fidelity Reynolds-averaged Navier-Stokes simulation are swept through a ground-fixed computational domain to initialize the wake. After the wake initialization, the large-eddy simulation of the vortical wake is performed until vortex decay. The methodology is tested with the NACA0012 wing and applied to the DLR-F6 wing-body model. The roll-up process of the vorticity sheet from a main wing and the merge of an inboard wing vortex into the wingtip vortex are simulated. Vortex parameters such as the radially averaged circulation, vortex core radius and vortex separation are also evaluated. The growth rate of the vortex core radius is relatively small during the roll-up where the fine mesh resolution in the LES is required to capture the tiny vortex core in the RANS simulation.

Misaka, T., Holzaepfel, F., and Gerz, T.

"LARGE-EDDY SIMULATION OF SPATIALLY DEVELOPING AIRCRAFT WAKE"

Eight International Conference on Flow Dynamics, November 2011, Sendai, Japan, pp. 274-275.

Development of aircraft's wake vortex from the roll-up until vortex decay is studied. An aircraft model and a surrounding flow field obtained from high-fidelity Reynolds Averaged Navier-Stokes simulation are swept through a ground fixed computational domain to initialize the wake. After initialization, large-eddy simulation of the vortical wake is performed until vortex decay, i.e., 2-3 minutes after the passage of aircraft. Here, the methodology and some results from the simulations using the DLR-F6 wing-body model are presented.

Misaka, T., Holzaepfel, F., Gerz, T., Manhart, M. and Schwertfirm, F.

"LARGE-EDDY SIMULATION OF WAKE VORTEX EVOLUTION FROM ROLL-UP TO VORTEX DECAY"

AIAA Paper No. 2011-1003, January 2011, Orlando, FL.

Large-eddy simulation (LES) of wake vortex evolution from vortex generation until decay is performed by combining Reynolds-averaged Navier-Stokes (RANS) simulation and LES. An aircraft model and a surrounding flow field obtained from high-fidelity RANS simulation are swept through a ground fixed computational domain to initialize the wake. After the initialization, time integration of the wake is performed until vortex decay (2-3 minutes). The present paper describes the approach and some results from the simulations where the aircraft is represented by the DLR-F6 wing-body model. The results show that moderate mesh resolution in the wake initialization phase results in lower vortex circulation of wake vortex after roll-up, although the overall distribution of vorticity is not sensitive to the mesh resolution. Boundary condition in the flight direction is one of the key points to continue the time integration of wake vortex after its initialization. Periodic boundary conditions used in this study induce disturbances propagating from boundaries into the computational domain, which leads to faster decay of wake vortex.

Misaka, T., Holzaepfel, F., Hennemann, I., Gerz, T., Manhart, M. and Schwertfirm, F.

"VORTEX BURSTING AND TRACER TRANSPORT OF A COUNTER-ROTATING VORTEX PAIR"

Physics of Fluids, Vol. 24, 2012, pp. 025104-1 - 025104-21.

Large-eddy simulations of a coherent counter-rotating vortex pair in different environments are performed. The environmental background is characterized by varying turbulence intensities and stable temperature stratifications. Turbulent exchange processes between the vortices, the vortex oval, and the environment, as well as the material redistribution processes along the vortex tubes are investigated employing passive tracers that are superimposed to the initial vortex flow field. It is revealed that the vortex bursting phenomenon, known from photos of aircraft contrails or smoke visualization, is caused by collisions of secondary vortical structures traveling along the vortex tube which expel material from the vortex but do not result in a sudden decay of circulation or an abrupt

change of vortex core structure. In neutrally stratified and weakly turbulent conditions, vortex reconnection triggers traveling helical vorticity structures which is followed by their collision. A long-lived vortex ring links once again establishing stable double rings. Key phenomena observed in the simulations are supported by photographs of contrails. The vertical and lateral extents of the detrained passive tracer strongly depend on environmental conditions where the sensitivity of detrainment rates on initial tracer distributions appears to be low.

Misaka, T., Kato, H., Ogasawara, T., Obayashi, S., Yamada, I. and Okuno, Y.

"MEASUREMENT-INTEGRATED SIMULATION OF WAKE TURBULENCE WITH FOUR-DIMENSIONAL VARIATIONAL METHOD"

Bulletin of the Japan Society for Industrial and Applied Mathematics, Vol. 19, Issue 3, 2009, pp. 150-162.

Realistic retrieval of aircraft wake turbulence at an airport is not straight-forward due to the difficulty in incorporating actual conditions such as an atmospheric boundary layer and a flight trajectory into the numerical simulation. In this study, the numerical simulation of wake turbulence is performed by integrating lidar measurements at Sendai airport. The four-dimensional variational method is employed for the integration with taking an actual measurement process into consideration. The behavior of wake turbulence under realistic wind conditions is shown after the discussion regarding the convergence of a retrieved flow field.

Misaka, T., Obayashi, S. and Jeong, S.

"UNCERTAINTY QUANTIFICATION OF LIDAR-DERIVED WAKE VORTEX PARAMETERS WITH/WITHOUT DATA ASSIMILATION"

AIAA Paper 2016-3271, June 2016, Washington, DC.

In this study, the uncertainty quantification of wake vortex parameters measured by a Doppler lidar is conducted to assess the errors of the lidar-derived parameters due to the measurement process. We employ three methods to estimate vortex parameters from lidar measurements: a simple method to detect velocity peaks on the measurement plane, and a least-square fitting of a vortex model to lidar velocity. In addition, wake vortex parameters along with a surrounding wind field are estimated based on the four-dimensional variational (4D-Var) method assuming a velocity field obtained by the Rosenhead-Burnham-Hallock vortex model. With the last approach, vortex parameters are obtained considering the factors such as insufficient resolution in the line-of-sight direction and vortex movement during a laser scan. It is confirmed from numerical experiments that the average circulation is significantly underestimated and core radius becomes too large with the simple method. The least-square fitting reduces the deviation of output/input parameter ratios. On the other hand, vortex parameters estimated with the help of the 4D-Var method are further improved by compensating the errors due to the measurement process.

Misaka, T., Obayashi, S., Stephan, A., Holzaepfel, F. and Gerz, T.

"SENSITIVITY ANALYSIS OF WAKE VORTEX PARAMETERS MEASURED BY DOPPLER LIDAR"

AIAA Paper 2015-3023, June 2015, Dallas, TX.

In this study, the sensitivity analysis of wake vortex parameters measured by a Doppler lidar is conducted to assess the errors due to the measurement process. To reduce the uncertainty caused by the measurement process as possible, wake vortex parameters along with a surrounding wind field are estimated based on the four-dimensional variational (4D-Var) method assuming a velocity field obtained by the Rosenhead-Burnham-Hallock vortex model. With this approach, vortex parameters are obtained considering the factors such as insufficient resolution in the line-of-sight direction and vortex descent during a laser scan. It is confirmed from numerical experiments that the average circulation is significantly underestimated when it is derived from the lidar measurement, while vortex core radius becomes too large in the lidar measurements. On the other hand, vortex parameters estimated with the help of the 4D-Var method appear sharply by compensating the errors due to the measurement process.

Misaka, T., Obayashi, S., Stephan, A., Holzaepfel, F., Gerz, T. and Nakahashi, K.

"NUMERICAL SIMULATION OF JET-WAKE VORTEX INTERACTION"

AIAA Paper 2014-0926, January 2014, National Harbor, MD.

The interaction of aircraft jet exhaust and wake vortex is numerically studied. Following the preceding numerical study of wake vortex evolution from roll-up until vortex decay, we aim to simulate the jet-vortex interaction from the early phase until the complete roll-up. For numerical simulation we employ an unstructured mesh Reynolds-averaged Navier-Stokes (RANS) solver for the near-field including the boundary layer around an aircraft, while a Cartesian mesh large-eddy simulation (LES) solver implemented on the framework of the Building-Cube Method (BCM) is used for the mid- to far-field wake development. Here we investigate a coupling approach of the above solvers to simulate the initial phase of jet exhaust and aircraft wake. The results show that a multi-level Cartesian mesh of the BCM is effective to capture the fine structure of aircraft wake including jet exhaust.

Misaka, T., Ogasawara, T., Obayashi, S., Yamada, I. and Okuno, Y.

"INTEGRATED SIMULATION OF WAKE TURBULENCE USING LIDAR MEASUREMENT"

5th World Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS), Venice, Italy, July 2008

The Electric Navigation Research Institute set a lidar system for wake turbulence measurements at Sendai Airport in Japan. From the viewpoint of the understanding of flow structure of wake turbulence, however, there are some drawbacks such as the lack of spatial resolution in the line-of-sight (LOS) direction and the difficulty in tracking tip vortices for long periods due to the disturbance of ambient wind. The lidar measurement at Sendai Airport is averaged every 30 m in the LOS direction.

This limitation is especially unfavorable because the core diameter of the wake vortex is in the order of several meters. For the consideration of an actual atmospheric condition in the numerical simulation, the present study attempts to integrate lidar measurements into the numerical simulation using data assimilation technique. Specifically, four-dimensional variational (4D-Var) method was applied to integrate lidar measurements with the three-dimensional computational fluid dynamics simulation, in which actual scanning processes of the lidar was simulated as a measurement operator of the 4D-Var method. And a bogus vortex technique was adopted to ensure the existence of a vortex pair in the flow field. The validation of the method was performed by idealized test cases using 'virtual' lidar measurement which was produced by the reference simulation of a vortex pair. Then, the method was applied to actual lidar measurements at Sendai Airport.

Misaka, T., Ogasawara, T., Obayashi, S., Yamada, I. and Okuno, Y.

"MEASUREMENT-INTEGRATED SIMULATION OF WAKE TURBULENCE"

AIAA Paper No. 2008-466, Reno, NV, January 2008

Large eddy simulation of wake turbulence was performed by integrating the lidar measurements. Four-dimensional variational method was applied to integrate lidar measurements with the three-dimensional large eddy simulation. In addition, a bogus vortex technique was adopted to ensure the existence of wake vortices in the flow field. The validation of the method was performed by idealized test cases using virtual lidar measurement which is produced by the reference simulation of a vortex pair. The results of the validation cases showed the convergence of vortex parameters such as a circulation to that of reference simulation case. It is also confirmed that the velocity distribution on a measurement plane agrees with reference one.

Misaka, T., Ogasawara, T., Obayashi, S., Yamada, I. and Okuno, Y.

"ASSIMILATION EXPERIMENT OF LIDAR MEASUREMENTS FOR WAKE TURBULENCE"

Journal of Fluid Science and Technology, Vol. 3, No. 4, 2008, pp. 512-518.

Numerical simulation of wake turbulence was performed by integrating the lidar measurements using four-dimensional variational method. A bogus vortex technique was adopted to ensure the existence of wake vortices in the flow field. The validation of the method was performed by an idealized test case using virtual lidar measurement which was produced by the reference simulation of a vortex pair. The results of the validation showed the convergence of a vortex parameter such as a circulation to the parameter of reference simulation case. It was also confirmed that the velocity distribution on a measurement plane agreed with the reference one.

Misaka, T., Yoshimura, R., Obayashi, S. and Matayoshi, N.

"LARGE EDDY SIMULATION OF WAKE VORTICES UNDER INFLUENCES OF HANGAR WAKE AND THE GROUND"

AIAA Paper 2018-2864, June 2018, Atlanta, GA.

Large eddy simulation of wake vortices in ground effect with realistic terrain around an airport was conducted focusing on the airport-specific behavior of wake vortices. We considered here a landing at Tokyo-Haneda airport in Japan, where a wake of hangar buildings covers landing paths under a certain wind condition. We developed a large eddy simulation code for adaptive mesh refinement capturing fine vortex core of wake vortex. Outer boundary conditions of the simulation were provided by the Weather Research and Forecasting (WRF) numerical prediction model to retrieve the wind condition. The impact of a crosswind over airport buildings on the behavior of wake vortex was evaluated by visualized images so far.

Mishra, A., Yadav, H., Djenidi, L. and Agrawal, A.

"EXPERIMENTAL STUDY OF FLOW CHARACTERISTICS OF AN OBLIQUE IMPINGING JET"

Experiments in Fluids, Vol. 61, Issue 3, March 2020, Article:90.

An experimental study has been performed by using particle image velocimetry to investigate the effect of nozzle-to-plate separation distance (L) and jet impingement angle on the flow characteristics of an obliquely inclined submerged water jet. Measurements were taken for $L/D = 1D, 2D, 4D$ and $6D$ (where D is the diameter of the nozzle) for the jet impingement angle (θ) of 45° and 26° , and the flow characteristics in the uphill and the downhill regions are investigated at Reynolds number of 2600 (based on the nozzle diameter D and the jet velocity U_0). It is observed that surface spacing has an opposite effect in the uphill and the downhill regions in terms of wall jet flow. In the uphill region, the tendency of the wall jet to grow increases with increase in L/D . However, in the downhill region, the jet velocity and it.

Mitchell, A. M., Barberis, D., Molton, P. and Delery, J.

"CONTROL OF LEADING-EDGE VORTEX BREAKDOWN BY TRAILING EDGE INJECTION"

Journal of Aircraft, Vol. 39, No. 2, March-April 2002, pp. 221-226.

The goal of this research is the control of the vortex breakdown locations over sharp-edged, slender, delta wings at high angles of attack. Water tunnel tests of a 75° delta wing examined symmetric and asymmetric trailing-edge jet injection as a method to control and delay the leading-edge vortex breakdown locations. These tests were accomplished at angles of attack between 20° and 40° at freestream velocities of 10 and 20 cm/s. Flow visualization data provide a description of the leading-edge vortices and of the vortex breakdown locations. The results demonstrate the ability of symmetric and asymmetric trailing-edge jet injection to control the leading-edge vortex breakdown locations. However, elevated trailing-edge injection mass flow rates create dramatic negative influences and accelerate vortex breakdown, especially for asymmetric flow control cases.

Mitchell, B. E., Lele, S. K. and Moin, P.

"DIRECT COMPUTATION OF THE SOUND FROM A COMPRESSIBLE CO-ROTATING VORTEX PAIR"

J. Fluid Mechanics, Vol. 285, 1995, pp. 181-202

The far-field sound generated by compressible co-rotating vortices is computed by direct computation of the unsteady compressible Navier-Stokes equations on a computational domain that extends to two acoustic wavelengths in all directions. The vortices undergo a period of co-rotation followed by a sudden merger. The directly computed far-field sound is compared to the prediction of the acoustic analogy due to Moehring (1978, 1979), a modified form of the analogy developed by Lighthill (1952), and an acoustic analogy derived by Powell (1964). All three predictions are in excellent agreement with the simulation. Results of far-field pressure fluctuations from an acoustically non-compact, co-rotating vortex pair are also presented. In this case, the vortex sound theory over-predicts the sound by 65% in accordance with the analysis of Yates (1978).

Mitchell, D. G.

"Fifty Years Of The Cooper-Harper Scale"

AIAA Paper 2019-0563, January 2019, San Diego, CA.

The year 2019 marks the fiftieth anniversary of the publication of a seminal document, The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, by George E. Cooper and Robert P. Harper, Jr. Despite taking a meager 52 pages to tell its story, NASA TN D-5153 manages to capture the essence of piloted evaluation of handling qualities. The Cooper-Harper handling qualities rating scale has withstood numerous attempts at improvement, simplification, or modernization, and even total replacement. With its continued use, we have learned that there are shortcomings in the scale, and that several of the terms used are not well-defined. Certainly, our interpretation of the scale has evolved over the past five decades. Yet it remains the standard tool for eliciting pilot opinion on aircraft handling qualities. This paper reviews the evolution of the usage of the scale, discusses its strengths and weaknesses, and demonstrates the value of the scale to handling-qualities evaluation for the foreseeable future.

Mitchell, G. A.

"EFFECT OF INLET INGESTION OF A WING TIP VORTEX ON TURBOJET STALL MARGIN"

NASA TM X-71610, September 1974, NASA Lewis Research Center, Cleveland, OH.

A two-dimensional inlet and J85-GE-13 turbojet engine were placed in a Mach 0.4 stream so as to ingest the tip vortex of a forward mounted wing. Results show that ingestion of a wing tip vortex by a turbojet engine can cause a large reduction in engine stall margin. The loss in stall compressor pressure ratio was primarily dependent on vortex location and rotational direction and not on total-pressure variations across the compressor face.

Mitchell, G. A.

"PRELIMINARY INVESTIGATION OF INLET INGESTION OF A WING TIP VORTEX"

NASA TM-X-68225, April 1973, NASA Lewis Research Center, Cleveland, OH

An inlet-coldpipe assembly was placed in a Mach 0.4 stream to ingest the tip vortex of a forward mounted wing. The strongest vortex was produced by a wing angle of attack of 11 degrees. The vortex displayed a tangential velocity of 57 percent of local stream velocity prior to entering the inlet and a tangential velocity of 25 percent of local velocity at the simulated compressor-face. The total-pressure-profiles measured by standard compressor-face rakes were changed by the presence of the vortex only at the highest inlet mass-flow ratios.

Mitchell, G. A.

"EFFECT OF INLET INGESTION OF A WING TIP VORTEX ON COMPRESSOR FACE FLOW AND TURBOJET STALL MARGIN"

NASA TM-X-3246, July 1975, NASA Lewis Research Center, Cleveland, OH

A two-dimensional inlet was alternately mated to a coldpipe plug assembly and a J85-GE-13 turbojet engine, and placed in a Mach 0.4 stream so as to ingest the tip vortex of a forward mounted wing. Vortex properties were measured just forward of the inlet and at the compressor face. Results show that ingestion of a wing tip vortex by a turbojet engine can cause a large reduction in engine stall margin. The loss in stall compressor pressure ratio was primarily dependent on vortex location and rotational direction and not on total-pressure distortion.

Mitchell, T. B. and Rossi, L. F.

"THE EVOLUTION OF KIRCHHOFF ELLIPTIC VORTICES"

Physics of Fluids, Vol. 20, 2008, pp. 054103-1 - 054103-12

A Kirchhoff elliptic vortex is a two-dimensional elliptical region of uniform vorticity embedded in an inviscid, incompressible, and irrotational fluid. By using analytic theory and contour dynamics simulations, we describe the evolution of perturbed Kirchhoff vortices by decomposing solutions into constituent linear eigenmodes. With small amplitude perturbations, we find excellent agreement between the short time dynamics and the predictions of linear analytic theory. Elliptical vortices must have aspect ratios less than $a/b = 3$ to be completely stable. At late times, unstable perturbations evolve to states consisting of filaments surrounding and connecting one or more separate vortex core regions. Even modes have two different evolution paths accessible to them, dependent on the initial phase.

Mitcheltree, R. A., Margason, R. J. and Hassan, H. A.

"EULER EQUATIONS ANALYSIS OF THE INITIAL ROLL-UP OF AIRCRAFT WAKES"

J. Aircraft, Vol. 23, No. 8, August 1986, pp. 650-655

A new approach has been developed to study the initial roll-up of aircraft wakes. This approach is based on the solution of the three-dimensional Euler equations subject to inflow and initial conditions predicted by a vortex-lattice method. Thus, solutions are limited to those flowfields generated by wings that are free of flow separation. Results are presented for four configurations: a rectangular wing with part span flap, a rectangular wing, a typical transport-type configuration, and a fighter configuration. In addition, an assessment of an 'unsteady two-dimensional analogy' was undertaken using the two-dimensional time-accurate Euler equation solutions in cross-flow planes. In general, predictions from the two-dimensional unsteady analogy coincided with the three-dimensional results, which were found to be in good agreement with available experimental data.

Mitkin, V. V., Prokhorov, V. E. and Chashechkin, Y. D.

"ACOUSTIC SOUNDING OF VORTEX RINGS IN A CONTINUOUSLY STRATIFIED FLUID"

Fluid Dynamics, Vol. 36, No. 6, 2001, pp. 934-943

The experimental simulation of solitary vortex rings in a stratified fluid performed using high-frequency echo-sounding and optical visualization methods shows that on the range from turbulent to laminar regimes the vortex is a volume inhomogeneity with a sound scattering cross-section is approximately equal to U^5 , where U is the translational velocity. The absolute value of the sound scattering cross-section is determined by the microscale component of the vortex microstructure, which is commensurable with the sounding sonic wave length.

Miyazaki, T. and Hunt, J. C. R.

"LINEAR AND NONLINEAR INTERACTIONS BETWEEN A COLUMNAR VORTEX AND EXTERNAL TURBULENCE"

J. Fluid Mech., Vol. 402, 2000, pp. 349-378

The structure of initially isotropic homogeneous turbulence interacting with a columnar vortex (with circulation and radius) idealized both as a solid cylinder and a hollow core model is analyzed using the inhomogeneous form of linear rapid distortion theory (RDT), for flows where the r.m.s. turbulence velocity is small compared with circulation/radius. The turbulent eddies with scale L are distorted by the mean velocity gradient and, over a distance L from the surface of the vortex, by their direct impingement onto it, whether it is solid or hollow. Calculation of the distortion of small-scale initially random velocity fields shows how the turbulent eddies, as they are wrapped around the columnar vortex, become like vortex rings, with similar properties to those computed by Melander & Hussain (1993) using a fully nonlinear direct numerical simulation. A mechanism is proposed for how interactions between the external turbulence and the columnar vortex can lead to non-axisymmetric vortex waves being excited on the vortex and damped fluctuations in its interior.

Miyazawa, M.

"A TWO-DIMENSIONAL MODEL FOR TRAILING VORTEX STRUCTURE"

AIAA Paper No. 2004-1075, Reno, NV, January 2004

In the analysis of trailing vortex's behavior with time, a fully rolled-up vortex pair, represented by Rankine's vortex, is used as a basic, starting-point vortex model. However, it is hard to predict the basic structure, specifically the core size that determines the maximum swirl velocity. Also, analytical, and experimental data reported to date show a wide variety of the vortex core size. The present paper proposes a simple, hypothetical vortex model that uniquely determines the trailing-vortex core size. It was developed by reviewing the classical lifting-line theory as well as the trailing-vortex rolling-up process, thereby considering the conservation laws. The present analytical results show that the free-vortex core size is independent of the aspect ratio for arbitrarily loaded wings. Also, sample calculations for representative commercial transport with elliptically loaded wings show that the core size increases as the aircraft becomes heavier while the maximum swirl velocity is practically unchanged.

Mocker, H. W. and Wagener, T. J.

"LASER DOPPLER OPTICAL AIR-DATA SYSTEM: FEASIBILITY DEMONSTRATION AND SYSTEMS SPECIFICATIONS"

Applied Optics, Vol. 33, No. 27, September 1994, pp. 6457-6472

A compact laser Doppler velocimeter with diode-pumped solid-state laser technology at 1.06 microns and a novel solid-block beam-splitting interferometer was demonstrated. This system allows for accurate Doppler velocity measurements even in a vibration environment. A comparison of the backscatter measurements with a backscatter sonde from the University of Wyoming showed excellent agreement. Based on demonstrated performance and technology projection, the system specifications of an optical air-data system at 2.015 microns are determined, and a detailed design concept is presented. In addition, the potential for a multifunctional sensor that can determine air data and detect wind shear and wake vortices is addressed.

Modi, A.

"REAL-TIME VISUALIZATION OF AEROSPACE SIMULATIONS USING COMPUTATIONAL STEERING AND BEOWULF CLUSTERS"

PhD Thesis, August 2002, The Pennsylvania State University, University Park, PA.

In this thesis, a new, general-purpose software system for computational steering has been developed to carry out simulations on parallel computers and visualize them remotely in real-time. The steering system is extremely lightweight, portable, robust and easy to use. As a demonstration of the

capabilities of this system, two applications have been developed. A parallel wake-vortex simulation code has been written and integrated with a Virtual Reality (VR) system via a separate graphics client. The coupling of computational steering of parallel wake-vortex simulation with VR setup provides us with near real-time visualization of the wake-vortex data in stereoscopic mode. It opens a new way for the future Air-Traffic Control systems to help reduce the capacity constraint and safety problems resulting from the wake-vortex hazard that are plaguing the airports today. In another application, an existing computational fluid dynamics code has been integrated with the steering system to enable interactive visualization of complex simulations from any remote workstation. Benefits of scalability and dimensional reduction arising from this approach have been imperative in the development of this system. This system makes the visualization of flow simulations easier, efficient, and most-importantly without any delay as and when the results are generated, thus giving the user much greater flexibility in interacting with the huge amounts of data. At a more basic level, the ability to get 'immersed' in the complex solution as it unfolds using the depth cue of the stereoscopic display and the near real-time nature of the computational steering system opens a whole new dimension to the scientists for interacting with their simulations.

Modi, A., Long, L. N. and Plassmann, P. E.

"REAL-TIME VISUALIZATION OF WAKE-VORTEX SIMULATIONS USING COMPUTATIONAL STEERING AND BEOWULF CLUSTERS"

5th International Meeting, High Performance Computing for Computational Science, Porto, Portugal, June 2002.

In this paper, we present the design and implementation of POSSE, a new, lightweight computational steering system based on a client/server programming model. We demonstrate the effectiveness of this software system by illustrating its use for a visualization client designed for a particularly demanding real-time application -- wake-vortex simulations for multiple aircraft running on a parallel Beowulf cluster. We describe how POSSE is implemented as an object-oriented, class-based software library and illustrate its ease of use from the perspective of both the server and client codes. We discuss how POSSE handles the issue of data coherency of distributed data structures, data transfer between different hardware representations, and several other implementation issues. Finally, we consider how this approach could be used to augment AVOSS (an air traffic control system currently being developed by the FAA) to significantly increase airport utilization while reducing the risks of accidents.

Modi, A., Long, L. N. and Plassmann, P. E.

"REAL-TIME VISUALIZATION OF WAKE-VORTEX SIMULATION USING COMPUTATIONAL STEERING AND BEOWULF CLUSTERS"

5th International Meeting, High Performance Computing for Computational Science, VEC PAR 2002, Lisbon, Portugal, June 2002

A general computational steering system has been developed to carry out simulations on parallel computers and visualize them remotely in real-time. The steering system is extremely lightweight, portable, robust and easy to use. As a demonstration of the capabilities of this system, a parallel wake-vortex simulation code has been written and integrated with our Virtual Reality setup via a separate graphics client. The coupling of computational steering of our parallel simulation with VR setup provides us with near real-time visualization of the wake-vortex data in stereoscopic mode. It opens a new way for the future Air-Traffic Control systems to help reduce the capacity constraint and safety problems resulting from the wake-vortex hazard that are plaguing the airports today. At a more basic level, the ability to get 'immersed' in the complex solution as it unfolds using the depth cue of the stereoscopic display and the real-time nature of the computational steering system opens a whole new dimension to the scientists for interacting with their simulations.

Moet, H.

"THE EFFECTS OF THE ATMOSPHERIC TURBULENCE ON WAKE VORTICES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Wake vortices are strongly affected by ambient atmospheric parameters such as wind shear, stratification, and turbulence as well as by the proximity of the ground. The lifespan of wake vortices may be short in presence of strong turbulence but may also be of the order of several minutes in case of weak turbulence. The vortex lifespan is an essential aspect in the issue of wake vortex encounters. In this study we focus on the effect of three-dimensional ambient atmospheric turbulence on vortex decay using temporal large eddy simulations. The effect of ambient atmospheric turbulence has been investigated by placing vortex systems in homogeneous isotropic turbulence, which is assumed to be either a good approximation of atmospheric turbulence as well as a suitable option for generic vortex/turbulence interaction studies. A large set of single vortex and vortex pair configurations has been considered in order to determine the quantitative and qualitative effects of ambient turbulence on the vortex dynamics. The different mechanisms that have been observed during the decay process are turbulent diffusion, the creation of azimuthal structures of vorticity, the concurrent exchange of vorticity between primary vortices and the surrounding turbulence, as well as occurrence of large deformation and the onset of instability processes. The circulation, which quantifies the strength of the vortex is significantly affected by the presence of turbulence, and an accompanying parameter study resulted in the identification of pertinent parameters governing the circulation decay. Based on the numerical simulations, a simple turbulence decay model is proposed as a function of the parameters characterizing the ambient turbulence. A second three-dimensional large eddy simulation code is used to simulate the behavior of aircraft wake vortices in a more realistic atmosphere. In this case, both weak turbulence and stratification effects are studied. Stable stratification is here a consequence of the earth's boundary layer activity. A system of vortices in post roll-up phase placed in a suitable meteorological background form the initial conditions of a temporal simulation. Mesh refinement techniques enable the use of a large computational domain to capture the different scales of motion present in the atmospheric boundary layer as well as a sufficient resolution in the region where the

vortices reside. Eventually, the decay processes identified in the homogeneous isotropic turbulence simulations and in the more realistic test case will be compared.

Moet, H. L. C., Darracq, D., Laporte, F. and Corjon, A.

"INVESTIGATION OF AMBIENT TURBULENCE EFFECTS ON VORTEX EVOLUTION USING LES"

AIAA Paper No. 2000-0756, Reno, NV, January 2000

The effects of ambient turbulence on vortex dynamics are studied using a validated, three-dimensional, large-eddy simulation model. The objective of this study is to understand the mechanisms of interaction between vortices and turbulence and to obtain quantitative data about the aging process. Numerical simulations are performed in order to isolate the effects of ambient turbulence on a configuration consisting of a single vortex or vortex pair. A set of simulations has been conducted by placing vortices in a field of homogeneous isotropic turbulence for a range of turbulence intensities. The results reveal typical phenomena of vortex/turbulence interaction such as gradual, quasi-linear circulation decay due to turbulent diffusion, vortex deformation, appearance of azimuthal vortical structures and the occurrence of long- and short-wavelength instabilities. Several parameter studies have been performed to quantify a critical parameter which affects the strength of vortices and/or predicts the occurrences of instabilities.

Moet, H. L. C., Laporte, F., Darracq, D. and Corjon, A.

"LARGE-EDDY SIMULATIONS OF VORTEX/TURBULENCE INTERACTION"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

The issue of aircraft wake vortices is directly related to two different aspects, namely the structure of the wake vortices themselves and the characteristics of the atmospheric turbulence surrounding them. The present study has focused on the dynamics of vortices interacting with turbulence. For this purpose, a single vortex or vortex pair configuration has been placed in homogeneous isotropic turbulence. Large-eddy simulations at realistic Re-number have been performed to study vortex decay. This has been achieved by varying parameters that govern either the vortex configuration or the turbulence. It was observed that the turbulence intensity and the vortex spacing were the main parameters that affect the decay. Furthermore, the role of the turbulence can be separated into two effects - on the one hand, it causes gradual decay due to the diffusive property of turbulence solely having a significant effect near the vortex core; on the other hand, the turbulence may trigger instabilities that lead to the accelerated decay of vortices.

Moet, H., Darracq, D. and Corjon, A.

"DEVELOPMENT OF A DECAY MODEL FOR VORTICES INTERACTING WITH TURBULENCE"

AIAA Paper No. 2001-0545, Reno, NV, January 2001

The result of recent LES simulations of vortices interacting with turbulence are used to define a simple turbulence decay model. The observations made during the analysis of the results showed the appearance of several phenomena that dominate the vortex decay. An accompanying parameter study resulted in the quantification of pertinent parameters such as the turbulence intensity, the integral length scale of the turbulence and the vortex separation. These parameters are incorporated in a new turbulence decay model that is best matched to the numerical simulation results.

Moet, H., Laporte, F., Chevalier, G. and Poinso, T.

"WAVE PROPAGATION IN VORTICES AND VORTEX BURSTING"

Physics of Fluids, Vol. 17, May 2005, pp. 054109-1 to 054109-15

The propagation of pressure waves in a Lamb-Oseen vortex has been investigated both by three-dimensional direct numerical simulations as well as a set of large-eddy simulations. The pressure wave is initiated by locally increasing the core radius of a Lamb-Oseen vortex at its edge. This wave travels along the vortex axis towards the region with a thinner core radius. Behind the wave the axial velocity increases so that sufficient swirl may trigger the helical instability. An abrupt change of flow structure in the vortex core is observed in the case of intersecting pressure waves: this phenomenon is known as vortex bursting. A vortex system composed of two symmetric counter-rotating vortices, which is similar to that of an aircraft has also been investigated by means of large-eddy simulations. In the far-field region the system develops linear instabilities such as the Crow instability, which is characterized by a large-scale symmetric sinusoidal deformation resulting in the reconnection of the two vortices. It also demonstrates the occurrence of helical instability and vortex bursting.

Moffatt, H. K.

"THREE COINS IN A FOUNTAIN"

Journal of Fluid Mechanics, Vol. 720, 2013, pp. 1-4.

If, in a large expanse of fluid such as air or water, an object that is heavier than the fluid displaced is released from rest, it descends in a manner that can depend in a complex way on its geometry and density (relative to that of the fluid), and on the fluid viscosity, which, as in other fluid contexts, remains important no matter how small this viscosity may be. A major numerical attack on this problem for the case in which the object is a thin circular disc is presented by Auguste, Magnaudet, and Fabre.

Mohan, A. T., Agostini, L., Gaitonde, D. V. and Garmann, D. J.

"STATISTICAL ANALYSIS AND MODEL REDUCTION OF SURFACE PRESSURE IN THE INTERACTION OF A STREAMWISE-ORIENTED VORTEX WITH A WING"

AIAA Paper 2015-3412, June 2015, Dallas, TX.

A streamwise oriented vortex can interact with a wing in numerous applications such as formation flight, where it offers advantages of higher lift and reduced drag, and turbomachinery blade-row interactions. High-fidelity simulations of such interactions are becoming more common, a recent example being those presented by Garmann and Visbal, who use a very high-order approach to analyze the effect of vortex impingement location on a rectangular wing at 4-degree angle-of-attack and Reynolds number of 20,000. These 3-D unsteady simulations generate immensely large datasets, making the effort to understand the underlying physics very challenging. Model reduction techniques have gained immense popularity not only to manage the data but also as an analysis tool. In this paper, we combine two such tools, specifically Empirical Mode Decomposition (EMD) and Dynamic Mode Decomposition (DMD), to analyze the surface pressure data from the simulations of Garmann and Visbal. It is shown that EMD and DMD can be used in conjunction with each other to study the footprint of a given flow feature on the surface. The study also discusses the relationship between the transient response of surface pressure and the incident streamwise vortex with some interesting observations pertaining to non-uniform wing-loading. The effectiveness of DMD to extract a small subset of the data which can capture the key features of unsteady pressure interactions is also demonstrated. The flow structures associated with the key frequencies identified by DMD are discussed with implication on the engineering aspects of interest.

Mohring, W.

"ON VORTEX SOUND AT LOW MACH NUMBER"

Journal of Fluid Mechanics, Vol. 85, Part 4, 1978, pp. 685-691.

A transformation is described which relates the sound generated by low Mach number flow to the flow vorticity. For compact flow fields the apparent sound source is of quadrupole type and linear in the vorticity and therefore also linear in the flow velocity. This scheme is applied to the sound generated by the interaction of two identical thin vortex rings. Then a flow field with several compact vortices is discussed. It is found that each vortex can be replaced acoustically by a dipole related to the impulse of the vortex, plus the quadrupole just mentioned plus a spherically symmetric sound source related to the energy of the vortex. An application to low Mach number free-space turbulence shows that the generated sound is related to the vorticity correlation tensor.

Moin, P.

"REVISITING TAYLOR'S HYPOTHESIS"

Journal of Fluid Mechanics, Vol. 640, 2009, pp. 1-4.

Taylor's hypothesis, relating temporal to spatial fluctuations in turbulent flows is investigated using powerful numerical computations by del Alamo and Jimenez. Their results cast doubt on recent interpretations of bimodal spectra in relation to very large-scale turbulent structures in experimental measurements in turbulent shear flows.

Moisy, F. and Petitjeans, P.

"PRESSURE MEASUREMENTS IN A STRETCHED VORTEX"

Lecture Notes in Physics, Vol. 555, 2000, pp. 252-262

We report new results obtained with a strong laboratory vortex, generated between rotating disks with an axial stretching, providing a model of strong vortex structures present in turbulent flows. We first characterize the strength of the vortex in this geometry by means of a global pressure measurement, and give direct evidence of a mechanism of stretching saturation due to strong rotation. Pressure measurements are then performed with a miniature probe sensor close to the vortex, in order to study the relevance of bulk measurements with small but invasive sensors. We analyze the influence of some geometric characteristics of the probe (size, distance from the vortex) on the measured pressure, together with the influence of the presence of a probe on the vortex strength. We briefly discuss consequences of these observations on pressure measurements in the bulk of turbulent flows.

Mokry, M.

"INTENSIFICATION OF AIRCRAFT WAKE VORTICES IN CROSSWIND SHEAR"

Journal of Aircraft, Vol. 40, No. 2, March-April 2003, pp. 405-407.

Based on the convection of thin vortex sheets, it was shown that aircraft vortices can temporarily intensify in the presence of crosswind shear.

Mokry, M.

"NUMERICAL SIMULATION OF AIRCRAFT TRAILING VORTICES INTERACTING WITH AMBIENT SHEAR OR GROUND"

Journal of Aircraft, Vol. 38, No. 4, July-August, 2001, pp. 636-643

A two-dimensional algorithm, based on the continuous vortex sheet method, is proposed for modeling the evolution and propagation of aircraft trailing vortices in a sheared environment. Among the phenomena discussed are the generation of secondary vortices, shear-layer instabilities, and interactions of trailing vortices with atmospheric and ground shear layers. Numerical simulations are produced by a code written as an interactive-graphics application for the Windows platform.

Mokry, M.

"THE VORTEX MERGER FACTOR IN AIRCRAFT WAKE TURBULENCE"

The Aeronautical Journal, January 2005, pp. 13-22

Vortex merger is studied within the context of two-dimensional discrete vortex sheets and demonstrated on two equally oriented circular vortices and aircraft tip and flap vortices. It is confirmed

that, depending on the wing load distribution, the latter may or may not coalesce into a single counter-rotating pair. The interaction of a vortex with an equally oriented shear layer, governed by the same physical principle, suggests a possible intensification of an aircraft vortex in cross-wind shear.

Mokry, M.

"HAZARD OF WAKE VORTEX ENCOUNTERS IN CROSSWIND SHEAR"

AIAA Paper No. 2003-0378, Reno, NV, January 2003

An interaction of aircraft wake vortices with a shear layer is investigated using the convection of vortex sheets in two space dimensions. Based on the numerical simulation results it is suggested that, in the presence of crosswind shear, one aircraft following another may be subjected to a stronger vortex than expected in the wake of the leading aircraft in a quiescent atmosphere. Suggestions are given on how to prevent creation of such vortices and how to avoid encountering them.

Mokry, M.

"AUGMENTATION OF AIRCRAFT WAKE VORTICES IN CROSSWIND SHEAR"

The 10th International Symposium on Flow Visualization, August 2002, Kyoto, Japan

Interactions of aircraft trailing vortices with crosswind shear are investigated using the method of discrete vortex sheets. Computer visualization reveals that equally-signed vorticity may combine to produce a vortex larger than the original wingtip vortex.

Mokry, M.

"NUMERICAL SIMULATION OF AIRCRAFT TRAILING VORTICES IN AN INTERACTIVE GRAPHICS ENVIRONMENT"

AIAA Paper No. 1999-0827, Reno, NV, January 1999

The motion of aircraft trailing vortices is simulated in the Windows graphics environment, using the C++ object-oriented approach. A time-efficient, physically meaningful modeling is provided by the continuous sheet method. Among the phenomena discussed are the generation of secondary vortices, shear layer instability and the interactions of trailing vortices with atmospheric and ground shear layers.

Mokry, M.

"REAL-TIME SIMULATION OF AIRCRAFT WAKE VORTICES"

Proceedings of the Fifth Annual Conference of the CFD Society of Canada, CFD Society of Canada, Victoria, May 1997, pp. 9-15 - 9-20

This paper demonstrates the usefulness of a computer live simulation in uncovering and understanding various physical phenomena accompanying the roll-up of vortex sheets. Among the observed and analyzed features are the contraction of the vortex sheet prior to the formation of an inboard vortex, instability, and irreversibility. Supplied by an on-line measurement of atmospheric conditions, the method can be extended to be used as a real-time simulation of aircraft wake vortices near the ground. The demonstration code has been written using the Graphics Device Interface (GDI) and the Object Windows Library (OWL) of Borland C++, Version 5.01.

Mokry, M. and Rainbird, W. J.

"CALCULATION OF VORTEX SHEET ROLL-UP IN A RECTANGULAR WIND TUNNEL"

J. Aircraft, Vol. 12, No. 9, September 1975, pp. 750-752

The note utilizes the concept of Green's functions to calculate the roll-up of a vortex sheet wake in a rectangular wind tunnel with solid walls. The computations are performed by the discretization of the continuous vortex sheet model by finite length elements which show more stable behavior than Westwater's array of point vortices. The results show that the vorticity distribution has essentially a stationary center of gravity, in marked contrast with the free air case where the center of gravity moves downwards.

Mokry, M. and Yeung, A. F. K.

"ON THE EVOLUTION OF TRAILING VORTEX SHEETS"

Proceedings of Third International Workshop on Vortex Flows and Related Numerical Methods, ESAIM, Vol. 7, 1999, pp. 292-303

The initial phase of the evolution of trailing vortex sheets is modelled using the continuous sheet method, corresponding to $Re = \infty$. In the proposed 2D numerical scheme, vorticity is conserved. A qualitative comparison of the numerically simulated results and low-speed data obtained by particle image velocimetry is provided. Among the phenomena discussed are the interactions of the trailing vortices with atmospheric and ground shear layers.

Mokry, M., Xu, H. and Yeung, A. F. K.

"EXPERIMENTAL AND NUMERICAL VISUALIZATION OF WING TRAILING VORTICES"

Proceedings of 9th International Symposium on Flow Visualization, Edinburgh, Scotland, August 2000, pp. 213-1-213-10

Wing trailing vortices are visualized both experimentally and computationally. The particle image velocimetry is applied to a half-wing tested in a low-speed wind tunnel. A numerical simulation of the vortices generated by a two-component wing is implemented using an Euler's equation solver. The separate C-grid topologies of the wing and flap are coupled using the chimera overlapping grid strategy. Vortex-specific physical phenomena, such as the initial rollup at wing tips and sub-vortex orbiting, are observed using an animated motion of fluid particles. Finally, a simple vortex sheet method, modelling potential flow in the cross-flow plane, is employed to study the development of the vortices and their interactions with atmospheric and ground shear layers. Presented are live computer simulations, showing the birth of secondary vortices and their interactive motion in crosswind.

Moldoveanu, C., Giovannini, A., Boisson, H.-C. and Moraru, F.

"NUMERICAL SIMULATION OF A LONGITUDINAL COUNTER-ROTATING VORTEX PAIR IN INTERACTION WITH GROUND"

Proceedings of the 5th IASME/WSEAS International Conference on Fluid Mechanics and Aerodynamics, August 2007, Athens, Greece, pp. 220-229.

Any object moving in the air leaves behind it a more or less organized wake vortex. In case of the aircraft, this wake results in a rolling up of flow starting from the ends of the wings. It is due to the lift of each wing and the generated vortex will be as much more intense as the lift increases. It can constitute a danger to another aircraft that flies in this wake, especially during takeoff and landing. In this case the wake vortex trajectories and strengths are altered by ground interactions. This study presents the results of a Large Eddy Simulation of wake vortex in ground effect providing the vorticity flux behavior.

Moldoveanu, C., Giovannini, A., Boisson, H.-C. and Somoia, P.

"SIMULATION OF WAKE VORTEX AIRCRAFT IN GROUND EFFECT"

INCAS - Bulletin, Vol. 3, Issue 1, 2011, pp. 55-61.

The problem developed in this paper is encountered in airplane aerodynamics and concerns the influence of long-life longitudinal wake vortices generated by wing tips or by external obstacles such as reactors or landing gears. More generally it concerns 3D bodies of finite extension in cross flow. At the edge of such obstacles, longitudinal vortices are created by pressure differences inside the boundary layers and rotate in opposite senses. It can constitute a danger to another aircraft that flies in this wake, especially during takeoff and landing. In this case the wake vortex trajectories and strengths are altered by ground interactions. This study presents the results of a Large Eddy Simulation of wake vortex in ground effect providing the vorticity flux behavior.

Moldoveanu, C.-E., Somoia, P., Ferrier, P. and Daude, H.

"MATHEMATICAL MODELS USED TO STUDY THE AIRCRAFT WAKE VORTICES"

Proceedings of the Scientific Conference AFASES 2013, May 2013, Brasov, Romania, pp. 671-676.

Developing air traffic and introducing large aircraft in use in the group of transport aircrafts has led to the necessity to optimize separation distances between aircrafts, especially near airports. These distances are imposed by airport safety and security conditions, related to the action of the wake turbulence generated by an aircraft on another. At the edge of the aircraft wings, longitudinal vortices are created by pressure differences inside the boundary layers and rotated in opposite senses. It can constitute a danger to another aircraft that flies in this wake, especially during take-off and landing. This paper presents the mathematical models used to simulate the aircraft wake vortex behavior.

Moldoveanu, C.-E., Somoia, P., Vedinas, I. and Ferrier, P.

"RESEARCHES CONCERNING AIRCRAFT WAKE VORTEX"

1st International Conference, New Challenges in Aerospace Sciences (NCAS 2013), November 2013, Bucharest, Romania.

An aircraft flying leaves behind it a more or less organized wake composed of persistent vortices, which constitute a danger for the following aircraft. To avoid this, the distances between aircrafts are imposed by airport safety and security conditions, related to the action of the wake turbulence generated by an aircraft on another. At the edge of the aircraft wings, longitudinal vortices are created by pressure differences inside the boundary layers and rotated in opposite senses. This study presents the modelling methods of the turbulence using Large Eddy Simulation and some applications in the case of wake vortex.

Moninger, W. R., Mamrosh, R. D. and Pauley, P. M.

"AUTOMATED METEOROLOGICAL REPORTS FROM COMMERCIAL AIRCRAFT"

Bulletin American Meteorological Society, Vol. 84, No. 2, February 2003, pp. 203-216.

Automated weather reports from commercial aircraft have been an important data source for numerical weather prediction (NWP) models for more than a decade, and have improved the forecasts from these models. More recently, direct access to these reports has become available to government weather forecasters and other researchers through a Web site operated by NOAA's Forecast Systems Laboratory (FSL). Direct access to these data has resulted in better quality control of the data, and more timely and accurate forecasts. We provide an overview of the kinds of aircraft data that are currently available, a brief history and overview of FSL's Web site and other data distribution mechanisms, a look at the use of the data in models, and examples of the use of these data in research and operational forecasting.

Monsch, S. C.

"A STUDY OF INDUCED DRAG AND SPANWISE LIFT DISTRIBUTION FOR THREE-DIMENSIONAL INVISCID FLOW OVER A WING"

MS Thesis, May 2007, Clemson University, Clemson, SC.

The purpose of this study was to validate an approach to estimating the induced drag on a finite wing by using a wake integral analysis. The long-term goal is related to developing an aerodynamic-structural systems integrated design methodology for wings using a transpiration boundary condition to control the spanwise lift distribution throughout a typical mission to minimize lift-induced drag. The short-term goal addressed by this study is to develop a methodology to extract accurate and robust calculations of the induced drag from second order numerical solutions. Numerical results for an untwisted, finite rectangular wing (NACA 0012, AR = 6.7) using no flap deflections are compared against theoretical lifting line predictions. The numerical approach used an Euler-based computational fluid dynamic (CFD) solver. An in-house lifting line code was used to predict the theoretical reference values. By dividing the wing into twenty span-wise sections and using a surface integral of pressure at each section, a span-wise lift distribution was extracted from the CFD solution. Under flow conditions representing subsonic and transonic flows (Mach 0.3 - 0.7) at small angles of attack, the comparison between the predicted numerical and lifting-line span-wise lift distributions show good agreement with a maximum deviation of only 2.4 percent over the wing span.

Montalvo, C. and Costello, M.

"META AIRCRAFT FLIGHT DYNAMICS"

Journal of Aircraft, Vol. 52, No. 1, January-February 2015, pp. 107-115.

A meta-aircraft is an air vehicle composed of a set of independent aircraft that are connected in flight to form a larger composite aircraft. This paper explores the dynamics of meta-aircraft systems with a focus on the changes in the aircraft flight dynamic modes and flexible modes of the system. Specifically, when aircraft are connected, basic flight dynamic modes such as the phugoid, short period, Dutch roll, spiral, and roll modes change as a function of the number of connected aircraft. For aircraft connected in a wing-tip-to-wing-tip configuration, the longitudinal modes remain largely invariant with respect to the number of aircraft, whereas lateral modes are variable for both tip-to-tail and wing-tip-to-wing-tip connection configurations. In addition, connected aircraft exhibit complex flexible modes that change based on the characteristics of the connection joint and the number of connected aircraft. These conclusions are reached using a rigid six-degree-of-freedom representation for a single aircraft, where aircraft are connected through a set of linear and rotational elastic elements modeling the connection mechanism. Aerodynamic loads from all lifting surfaces are computed using a nonlinear lifting-line approach to enable aerodynamic wake interactions between connected aircraft.

Montreuil, E., Ghedhaifi, W., Chmielarski, V., Vuillot, F., Gand, F. and Loseille, A.

"NUMERICAL SIMULATION OF CONTRAIL FORMATION ON THE COMMON RESEARCH MODEL WING/BODY/ENGINE CONFIGURATION"

AIAA Paper 2018-3189, June 2018, Atlanta, GA.

Aircraft contrails may contribute to the global radiative forcing. In this context, the investigation of contrail formation in the near field of an aircraft may be helpful in developing strategies to reduce undesirable impacts. Contrail formation is also a complex topic, since several physical processes are involved, covering a large range of space and time scales, from the engine exit to the atmospheric global scale. In the near field of the aircraft, contrail formation is mainly dominated by microphysics and mixing processes between the propelling jets and the external flow (the so-called jet-vortex interaction). In this study, three-dimensional Reynolds-Averaged Navier-Stokes (RANS) simulations of contrails produced by the Common Research Model wing/body/engine configuration during cruise flights is performed. In the present work, a dedicated internal nozzle geometry has been designed to replace the through flow nacelle of the original CRM configuration. Thus, the engine core and bypass flows are computed in the simulations, which allows several parametrical studies and avoids using parameterizations to describe the plume's dilution. The objective is to simulate the early development of contrails in a fresh plume whose dilution is obtained with a spatial simulation of jet/vortex interaction. A coupling is carried out with a chemical and a microphysical model implemented in the unstructured Navier-Stokes CFD code CEDRE to simulate particle growth using an Eulerian approach. The implemented microphysics model can simulate water condensation onto soot particles, considering their adsorption of sulfur species. In this context, an adaptation grid mesh procedure has been used to generate an optimized unstructured mesh in the fluid zone of interest (i.e. vortex wake and jet exhaust).

Mook, D. T., Roy, S., Choksi, G. and Dong, B.

"NUMERICAL SIMULATION OF THE UNSTEADY WAKE BEHIND AN AIRFOIL"

J. Aircraft, Vol. 26, No. 6, June 1989, pp. 509-514

The unsteady wake behind an airfoil is simulated numerically by a system of discrete vortex cores, also called point vortices. In common with previously developed procedures, at each time step a core is added to the wake at the trailing edge, and the cores already in the wake are convected at the local particle velocity. The innovation of the present method is that, as the cores begin to separate, more cores are added to the system and the circulations around the individual cores are reduced according to a linear interpolation routine. The spacing between cores is maintained approximately while the total circulation around the wake and airfoil is maintained exactly. In several examples, one finds qualitative agreement between computed wake shapes and flow visualization. The method shows promise as a means of simulating unsteady, closely coupled aerodynamic interference.

Moore, D. W.

"FINITE AMPLITUDE WAVES ON AIRCRAFT TRAILING VORTICES"

Aero. Quarterly, Vol. 23, November 1972, pp. 307-314

Numerical methods are used to study the growth of waves of finite amplitude on a pair of parallel infinite vortices. The vortices are treated as lines except in so far as the detailed structure of the core is needed to remove consistently the singularity in the line integrals for the velocities of the vortices. It is shown that the velocities eventually touch and the shape of the wake at this instant is calculated. The wave is quite distorted at this instant, but it is shown that its gross properties are given roughly by linear theory.

Moore, D. W.

"A NUMERICAL STUDY OF THE ROLL-UP OF A FINITE VORTEX SHEET"

J. Fluid Mech., Vol. 63, Part 2, April 1974, pp. 225-235

A point-vortex representation is used to study numerically the evolution of an initially plane vortex sheet. By introducing a tip vortex to represent the tightly rolled portion of the vortex sheet, the chaotic motion which was a feature of some earlier studies is eliminated and the details of the outer portion of the spiral are calculated. The rate of rolling up is calculated and is shown to be governed by the analytically predicted similarity law of Kaden during the initial stages of the rolling up. The calculations are continued until 99% of the vorticity has been rolled up, at which stage the spiral displays a marked ellipticity.

Moore, D. W.

"THE DISCRETE VORTEX APPROXIMATION OF A FINITE VORTEX SHEET"

AFOSR-TR-72-0034, October 1971, California Institute of Technology, Pasadena, CA

It is shown by examination of a special case of aircraft trailing vortices that the approximation of replacing a finite vortex sheet by an array of line vortices can be unreliable regardless of how many vortices are used.

Moore, D. W. and Saffman, P. G.

"THE INSTABILITY OF A STRAIGHT VORTEX FILAMENT IN A STRAIN FIELD"

Proceedings of the Royal Society of London, Series A - Mathematical and Physical Sciences, Vol. 346, No. 1646, 1975, pp. 413-425

A straight infinite vortex of finite cross section is deformed by the action of weak irrotational plane strain. The deformed vortex is shown, in the absence of axial flow, to be unstable to disturbances whose axial wavelengths lie in a narrow band, whose width is proportional to the imposed strain. The band is centered on the wavelength of the helical wave which does not propagate on the unstrained circular vortex. Thus support is given to the instability mechanism proposed recently by Widnall, Bliss and Tsai. The argument depends, however, on the mirror image of the helical wave also being a possible non-propagating disturbance on the unstrained vortex.

Moore, D. W. and Saffman, P. G.

"AXIAL FLOW IN LAMINAR TRAILING VORTICES;"

Proc. Royal Soc. London, Vol. 333, Series A, June 1973, pp. 491-50.

The structure of laminar trailing vortices behind a lifting wing is considered. The inviscid roll up of the trailing vortex sheet is examined, and the nature of the singularity at the center of the spiral is determined. It is shown that viscosity removes the singularity and the structure of the viscous core is obtained. The pressure in the viscous core is found and used to calculate the axial velocities produced by streamwise pressure gradients. It is found that the perturbation of axial velocity can be either away from the wing or towards the wing depending on the distribution of tip loading on the wing. For elliptic loading, the perturbation is towards the wing. The axial flow deficit in the core due to the boundary layers on the wing is also estimated. A comparison with experiment is made and reasonable agreement is found.

Moore, D. W. and Saffman, P. G.

"STRUCTURE OF A LINE VORTEX IN AN IMPOSED STRAIN"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 339-354

The velocity of a vortex line depends on its structure, i.e., the shape of the cross-section and the detailed vorticity distribution. As a first step towards an understanding of how the structure depends on the motion and the construction of a valid approximation for the motion of vortex lines in general flow fields, the structure of straight-line vortices in a uniform two-dimensional straining field is considered. Two cases are considered in detail; irrotational strain and simple shear.

Moore, D. W. and Saffman, P. G.

"THE MOTION OF A VORTEX FILAMENT WITH AXIAL FLOW"

Phil. Trans. Royal Soc. London, Vol. 272, No. 1226, July 1972, pp. 403-429

Infinitesimal waves on a uniform vortex flow is studied. The equation for the frequency of helical waves is obtained, and solved for the case of long waves which leave the internal structure almost unaltered. A method is developed to obtain results for vortices of non-uniform structure and for displacements which are not necessarily small compared with the core radius. The approach consists of balancing the Kutta-Joukowski lift force, the momentum flux due to the axial motion, and the tension of the vortex line. A general equation for the motion of a vortex filament is obtained, valid for arbitrary shape and internal structure, and in the presence of an external irrotational velocity field. When the axial flow vanishes, the method is equivalent to using the Biot-Savart law for the self-induced velocity with a suitable cutoff.

Moore, M. D.

"WAKE VORTEX WINTIP-TURBINE POWERED CIRCULATION CONTROL HIGH-LIFT SYSTEM"

Circulation Control Workshop, Hampton, VA, March 2004, pp. 641-656

A synergistic technology set is proposed that would use Circulation Control (CC) trailing edge blowing coupled to a wake vortex powered wingtip-turbine air compressor. This technology would provide small aircraft with the ability to take off and land in shorter distances, while achieving greater efficiency at the cruise condition; or takeoff and land at equivalent speeds and distances as today with a smaller wing and higher wing loading. Circulation Control has been investigated for over 30 years and shown to be very effective in increasing the wing maximum lift coefficient in tests of commercial transport and fighter aircraft vehicles. However, one of the significant penalties associated with CC systems is the power required to supply the source blowing air. Another part of this problem is that the CC mass flow required per pound of aircraft, and therefore the pneumatic power required, is proportional to the square of the takeoff velocity. Applying CC systems to aircraft that takeoff and land at relatively high speeds, such as commercial transports and fighters that are on the order of 120 knots, requires significant blowing power. Applying a CC system to GA aircraft that takeoff and land at speeds of about 60 knots, would require lower mass flows and are potentially a better fit for this technology. GA aircraft currently suffer from poor cruise efficiencies because the wing areas are sized by the takeoff and landing condition, making the wing approximately twice as large as required for efficient cruise. In addition, over sizing the wing to meet takeoff and landing results in low wing loading which is much more susceptible to turbulence, resulting in poor ride quality compared to higher wing loadings.

Morales, F. and Squires, K. D.

"SIMULATION OF ROTOR VORTEX INTERACTIONS WITH A PARTICLE-LADEN TURBULENT BOUNDARY LAYER"

AIAA Paper No. 2011-4041, June 2011, Honolulu, Hawaii.

Rotorcraft operation in austere environments can result in difficult operating conditions, particularly in the vicinity of sandy areas. The uplift of sediment by rotorcraft downwash, a phenomenon known as brownout, hinders pilot visual cues and may result in potentially dangerous situations. Brownout is a complex multi-phase flow problem that is not unique and depends on both the characteristics of the rotorcraft and the sediment. The lack of fundamental understanding constrains models and limits development of technologies that could mitigate its adverse effects. This provides the over-arching motivation of the current work focusing on models of particle-laden sediment beds. The particular focus of the current contribution is numerical modeling of near-surface fluid-particle interactions in turbulent boundary layers. Simulations are performed with and without coherent vortices superimposed on the background flow to understand the influence of rotorcraft downwash. The objectives are to gain insight into the fluid-particle dynamics that influence transport near the bed by analyzing the competing effects of the vortices, inter-particle collisions, and gravity. The computations are performed using an Euler-Lagrange approach in which a fractional-step method is applied to the fluid and with the particulate phase modeled using Discrete Particle Simulation. Following the

introduction of coherent vortices into the domain, the structures substantially distort the boundary layer, increasing the wall shear stress and raising kinetic energy levels of the turbulence. The fluid phase then returns to equilibrium as the vortices dissipate further downstream.

Moreira, J. and Johari, H.

"DIRECT MEASUREMENT OF DELTA WING VORTEX CIRCULATION USING ULTRASOUND"

AIAA Paper No. 1997-0743, January 1997, Reno, NV.

The circulation around a closed path encompassing the primary vortex of stationary delta wings is investigated using ultrasound. Ultrasonic pulses were propagated clockwise and counterclockwise along a fixed, closed path which was positioned perpendicular to the delta wing root chord lines. Circulation in the plane of the closed path was then determined from the transit time difference between the clockwise and counterclockwise pulses. Half-delta wings of 60- and 70-deg sweep angle were tested over a range of angles of attack from 2 to 38 deg and from 2 to 52 deg, respectively, in 20 increments, and at distances of 35, 50, 65, and 80 percent root chord from the wing apexes. Circulation behavior was examined as it relates to these parameters and to primary vortex burst location. Circulation was measured to grow nonlinearly with angles of attack for which the burst point remained downstream of the wing planform; circulation then increased in an approximately linear manner with increasing angle of attack until the burst point reached the vicinity of the wing apex. Circulation was found also to increase approximately linearly with increasing chordwise location at constant angles of attack.

Morillo, J. A. and Peters, D. A.

"VELOCITY FIELD ABOVE A ROTOR DISK BY A NEW DYNAMIC INFLOW MODEL"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 731-738.

The potential flow equations are converted to ordinary differential equations through a Galerkin approach in which velocity and pressure potential functions are expanded in terms of closed-form solutions to Laplace's equation. Because the method gives differential equations for the flow in terms of a relatively few generalized coordinates that represent modes of the flowfield, the resultant equations can be used effectively in preliminary design, real-time simulations, and dynamic eigenvalue analysis for aeroelasticity. This new theory is more general than the Peters-He dynamic wake model because it has a more rigorous derivation and includes inflow modes previously neglected in the Peters-He model. Results are presented in the frequency domain for simple harmonic motion. The complete velocity field above the disk is obtained by this new methodology, for axial and skewed flows, for various skew angles, and for different pressure distributions and are compared with the Peters-He model and with an exact solution obtained by a convolution integral.

Morozov, V. V. and Kalyadina, T. V.

"GREEN'S MODEL OF CYLINDRICAL VORTEX DECAY"

Computational Math. And Modeling, Vol. 19, No. 2, 2008, pp. 186-194. [Translated from Prikladnaya Matematika I Informatika, No. 25, 2007, pp. 70-80.]

Modeling vortex decay is essential for estimating the risk that during landing an aircraft will hit the wake vortex from a preceding aircraft. The relevance of this problem has increased due to the growing traffic in airports and the development of vortex forecasting systems. Green's model, one of the models describing the decay of point vortices, is generalized in this article to cylindrical vortices.

Morris, C., Peters, J. and Choroba, P.

"VALIDATION OF THE TIME BASED SEPARATION CONCEPT AT LONDON HEATHROW AIRPORT"

10th USA/Europe Air Traffic Management Research and Development Seminar (ATM2013), June 2013, Chicago, IL.

Headwind conditions on final approach cause a reduction in the landing rate which impacts not only the achieved capacity, but also the predictability of operations, time and fuel efficiency, and the environment (emissions). The ground speed reduction in headwind conditions results in an increase in the time spacing between each arrival pair for distance-based separations. The Time-Based Separation (TBS) concept changes the separation rules on final approach from distance based to time based to stabilize the time spacing between arrival pairs across headwind conditions to recover the lost landing rate currently experienced. This paper presents the key results of the final research phase of the validation of the TBS concept. This validation has been conducted in the framework of the SESAR Development phase project P6.8.1 Flexible and Dynamic Use of Wake Turbulence Separations. The work started in 2010 and is about to be finalized in February 2013 achieving pre-industrial development (V3) maturity level. The project has developed and assessed both the generic TBS concept and a local adaptation of the concept to the London Heathrow operating environment. The scope of the paper is focused on the validation of the concept for London Heathrow airport covering the real-time simulation results and the wake turbulence safety data analysis results.

Morris, D. J. and Holbrook, G. T.

"BASIC RESEARCH IN WAKE VORTEX ALLEVIATION USING A VARIABLE TWIST WING"

The 1980 Aircraft Safety and Operating Problem, Part 2, NASA Langley Research Center, March 1981, pp. 409-423

The variable twist wing concept was used to investigate the relative effects of lift and turbulence distribution on the rolled-up vortex wake. Several methods of reducing the vortex strength behind an aircraft were identified. These involve the redistribution of lift spanwise on the wing and drag distribution along the wing. Initial attempts to use the variable twist wing velocity data to validate the WAKE computer code have shown a strong correlation, although the vorticity levels were not exactly matched.

Morris, D. J., Croom, C. C., Holmes, B. J., and Van Dam, C.P.

"NASA AERIAL APPLICATIONS WAKE INTERACTION RESEARCH"

Paper AA-82-005, American Society Agricultural Engineers and National Agricultural Aviation Association, Las Vegas, December 1982

A computer code has been developed for predicting trajectories of particles released in the wakes of airplanes or helicopters. The code accounts for effects of turbulence, crosswind, propeller slipstream, terrain variations, and plant canopy density on particle trajectories. Comparisons are given between experiments and theory. Applications of the code for spray pattern improvement are illustrated.

Morris, J. P.

"EFFECT OF ADDING VORTEX ATTENUATING SYSTEMS ON THE DESIGN, PERFORMANCE, AND OPERATIONS OF A HEAVY COMMERCIAL JET TRANSPORT"

Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, June 1977, DOT Transportation Systems Center, Cambridge, MA, pp. 229-24.

Various trailing vortex attenuation concepts have been proposed for use on heavy jet transports. A preliminary investigation of the effects of several of these concepts on the design, performance, and operations of a model 747-200 airplane has been conducted. Three of these concepts that have been judged to be potentially feasible have been selected for this presentation: retractable splines, modified approach flaps (30 deg. inboard, 0 deg. outboard), and flight spoiler deflection. The effectiveness of these devices in alleviating the wake vortices is not addressed; the discussion is limited to the impact on airplane design requirements and resulting performance characteristics.

Morris, P. J., McLaughlin, D. K., Gabrielson, T. B. and Boluriaan, S.

"THE DEVELOPMENT OF A PLAN FOR THE ASSESSMENT, IMPROVEMENT AND DEPLOYMENT OF A RADAR ACOUSTIC SOUNDING SYSTEM (RASS) FOR WAKE VORTEX DETECTION"

Report 2005-0176054, September 2004, Penn State Univ., University Park, PA.

This report describes the activities completed under a grant from the NASA Langley Research Center to develop a plan for the assessment, improvement, and deployment of a Radar Acoustic Sounding System (RASS) for the detection of wake vortices. A brief review is provided of existing alternative instruments for wake vortex detection. This is followed by a review of previous implementations and assessment of a RASS. As a result of this review, it is concluded that the basic features of a RASS have several advantages over other commonly used wake vortex detection and measurement systems. Most important of these features are the good fidelity of the measurements and the potential for all weather operation. To realize the full potential of this remote sensing instrument, a plan for the development of a RASS designed specifically for wake vortex detection and measurement has been prepared. To keep costs to a minimum, this program would start with the development an inexpensive laboratory-scale version of a RASS system. The new instrument would be developed in several stages, each allowing for

a critical assessment of the instrument's potential and limitations. The instrument, in its initial stages of development, would be tested in a controlled laboratory environment. A jet vortex simulator, a prototype version of which has already been fabricated, would be interrogated by the RASS system. The details of the laboratory vortex would be measured using a Particle Image Velocimetry (PIV) system. In the early development stages, the scattered radar signal would be digitized and the signal post-processed to determine how extensively and accurately the RASS could measure properties of the wake vortex. If the initial tests prove to be successful, a real-time, digital signal processing system would be developed as a component of the RASS system. At each stage of the instrument development and testing, the implications of the scaling required for a full-scale instrument would be considered. It is concluded that a RASS system, developed for the specific application of wake vortex detection, could become part of a robust Aircraft Vortex Spacing System (AVOSS). This system, in turn, could contribute to Reduced Spacing Operations (RSO) in US airports and improvements in Terminal Area productivity (TAP).

Morris, S. and Williamson, C. H. K.

"FORMATION OF MINI VORTEX RINGS ARISING FROM A VORTEX PAIR IMPINGING ON A WAVY WALL"

69th Annual Meeting of the APS Division of Fluid Mechanics, November 2016, Portland, OR.

In this work, we examine the impingement of a counter-rotating vortex pair onto a wavy wall. When a vortex pair with the long-wave 'Crow' instability interacts with a flat boundary, the topology of the pair changes. This results in rebounding vortical structures whose form is dependent on the extent of the instability prior to wall interaction. By considering the 'complementary' experiment of a straight vortex pair encountering a wavy wall (rather than a wavy vortex pair impinging on a flat wall), certain critical features of the two flows are found to be similar. Such research has applications in fundamental turbulence, and in flows such as wingtip vortices generated behind aircraft.

Morrison, R.

"GROUND JET BLAST HAZARD"

NASA ASRS Directline, Issue No. 6, August 1993.

A high-level description on the importance of jet blast is given herein. A summary of the incident reports related to jet blast was presented.

Morton, B. R.

"THE STRENGTH OF VORTEX AND SWIRLING CORE FLOW"

J. Fluid Mech., Vol. 38, Part 2, September 1969, pp. 315-333

This note presents a discussion of the roles of axial momentum flux, flow force, angular momentum flux and circulation in determining the strength and hence characterizing the structure of such narrow

rotating axisymmetric core flows as swirling jets, vortex jets, sink vortices and vortex wakes. The salient (though sometimes neglected) features of these core flows are that perturbation pressure plays an essential role both in the coupling of axial and azimuthal velocity fields and in the transmission of force along the core, and that flux of angular momentum is invariant only along cores with zero gross circulation. Several existing solutions are brought into relationship by the discussion, including Long's similarity solution for draining vortices and Reynolds' dimensional treatment of swirling wakes.

Morton, T. S.

"THE VELOCITY FIELD WITHIN A VORTEX RING WITH A LARGE ELLIPTICAL CROSS-SECTION"

J. Fluid Mech., Vol. 503, 2004, pp. 247-271

The velocity field within a steady toroidal vortex is found for arbitrary mean core radius and section ellipticity. The problem is solved by transforming to coordinates that define invariant sets. The method allows the properties of the coordinate system metric tensor to be exploited in the continuity equation to obtain the solution. The vorticity is found to decrease monotonically with distance from the symmetry axis. For a given outer radius and outer perimeter velocity, the circulation of the vortex ring can be either smaller or larger than that of Hill's spherical vortex.

Morvant, R., Badcock, K. J., Barakos, G. N. and Richards, B. E.

"AIRFOIL VORTEX INTERACTION USING THE COMPRESSIBLE VORTICITY CONFINEMENT METHOD"

AIAA Journal, Vol. 43, No. 1, January 2005, pp. 63-75

The phenomenon of blade-vortex interaction (BVI) is central to the study of rotorcraft aerodynamics and aeroacoustics. The numerical simulation of BVI is challenging because most numerical schemes tend to alter the characteristics of the vortex, which must be preserved until the interaction. The compressible vorticity confinement method (CVCM) can preserve vortices and requires minimal modifications to existing computational-fluid-dynamics codes. Inviscid and viscous calculations using a range of turbulence models have been carried out for a well-known, head-on BVI case. This is the first time CVCM is employed for turbulent flow calculations with an upwind solver. The results obtained using the CVCM show a good agreement with measurements.

Mosher, M. C.

"A METHOD FOR COMPUTING THREE-DIMENSIONAL VORTEX FLOWS"

Zeitschrift fur Flugwissenschaften und Weltraumforschung, Vol. 9, May-June 1985, pp. 125-133

A new vortex method is presented for computing incompressible, inviscid, three-dimensional fluid flows. It is pointed out that this method has the convenient numerical properties of the two-dimensional vortex method, and, for this reason, is ideally suited for computing fluid flows in many problems of aerodynamic and hydrodynamic interest. Thus, jets and concentrated wake vortices can

be studied, considering wing-tip, strake, nose, and horseshoe vortices. The bookkeeping efforts involved in extending this method to a consideration of viscous effects are not very great, and the discussed procedure has, therefore, an advantage over the vortex filament method. Another advantage is related to the absence of requirements for the tracking of a finite difference grid. The considered method was successfully tested with respect to three problems.

Moss, S. J.

"THE TESTING AND VERIFICATION OF CONTRAIL FORECASTS USING PILOT OBSERVATIONS FROM AIRCRAFT"

Meteorol. Appl., Vol. 6, 1999, pp. 193-200.

Contrail forecasting techniques used within the UK Meteorological Office have changed little since the early 1940s and there has been no formal verification of the results. Recent research has shown that old forecasting techniques may not be wholly applicable to modern aircraft that now use more efficient engines. To compare the performance of both the old and the new forecasting techniques a validation trial was carried out over a nine-month period in which RAF pilots reported when and where contrails did and did not occur. These observations were compared with the predicted contrail levels from both the old and newer forecasting techniques. The results indicate that both techniques give a similar performance and that neither significantly out-perform a simple persistence prediction.

Mostafa, S., Bose, S., Nair, A., Raheem, M. A., Majeed, T. and Mohammed, A.

"A PARAMETRIC INVESTIGATION OF NON-CIRCULAR SPIROID WINGLETS"

EPJ Web of Conferences, Vol. 67, 2014, pp. 02077-1 to 02077-6.

This paper will present the study about Spiroid winglets and will go through its theoretical significance as well as the processes involved in the selection of an optimum aerodynamic design (configuration) of the spiroid that produced efficient aerodynamic performance results in terms of mainly Lift to Drag ratio (L/D), Induced drag, Chordwise and Spanwise Pressure distributions, Vorticity formation and strength comparison (between a simple wing, simple winglet and the spiroid with the best performance results) by varying several parameters and by comparing detailed Computational Fluid Dynamics Analyses on every design under cruise conditions. Consequently, the research conducted in this paper concluded that the spiroid exhibit better performance numbers upon comparison with its other options in terms of vortex reduction and overall drag reduction.

Moulden, T. H. and Frost, W.

"EFFECTS OF FOG DROPLETS ON WAKE VORTEX DECAY RATE"

NASA CR-2758, October 1976, Univ. Tennessee Space Institute, Tullahoma, TN

A simple model for the motion of particles in a laminar line vortex is discussed. The energy required to accelerate a set of these particles was determined and shown to be only a small fraction of the energy content of the vortex flow. It is shown that this energy transfer is unlikely to be sufficient to significantly modify the vortex decay rate. It is further argued that the effect of the particle on the viscous properties of the resulting two-phase fluid leads to a slower decay rate than in single phase air flow. However, this conclusion may not necessarily follow for turbulence flows. Results show that the migration of particles to the outer flow results in a redistribution of the velocity profile in the vortex and in a non-uniform two phase viscosity across the core. It is suggested that these effects may accelerate vortex bursting.

Moussa, C. and Carley, M. J.

"A LAGRANGIAN VORTEX METHOD FOR UNBOUNDED FLOWS"

International J. Numerical Methods in Fluids, John Wiley and Sons Ltd., 2008

A technique is presented for velocity calculations on the highly distorted node distributions typical of those found in Lagrangian vortex methods. The method solves the partial differential equation for stream function directly on the nodes, via a sparse, symmetric system of equations that can be solved using standard iterative solvers. When implemented in a triangulated vortex method, the technique gives computation times which scale as N to power 1.23, where N is the number of nodes. The computation scheme is derived for two-dimensional problems and applied to the prediction of the evolution of perturbed multipole vortices.

Mowforth, E.

"DETAILS OF MEASUREMENTS IN A TURBULENT TRAILING VORTEX"

Aero. Quarterly, Vol. 10, May 1959, pp. 161-162

The vortex was produced by an untwisted rectangular wing, which was mounted as a half-model in the middle of the wall of the low-speed wind tunnel at Cambridge University. Measurements were made of total pressure, angle of upwash, and static pressure.

Mudkavi, V. Y.

"THE PHENOMENON OF VORTEX BREAKDOWN"

Proceedings of the Fluid Dynamics Symposium in Honour of Professor R. Narasimha on his 60th Birthday, July 1993, Sikkim, India, pp. 123-135.

Vortex breakdown is an abrupt change of flow structure that occurs in swirling flows. More than 3 decades of research in this area has not shed light upon this very basic fluid dynamical phenomenon. The mechanism that leads to vortex breakdown is very poorly understood despite numerous theoretical and experimental investigations. There is still a need for a coherent theory. In this paper

these issues are considered in the form of a review of current literature on the phenomenon of vortex breakdown. Some existing criteria to predict the breakdown are presented.

Mudukutore, A. S. and Marshall, R. E.

"SIMULATION OF RADAR OBSERVED WINGTIP GENERATED WAKE VORTICES IN FOG"

Proceedings 28th Conf. on Radar Meteorology, American Meteorology Society, Austin, TX, September 1997, pp. 161-162

The present radar simulation attempts to model aircraft wingtip wake vortex returns in the presence of ground clutter and noise. The reflectivity model used assumes backscattering from a rain and cloud-droplet Rayleigh target environment. A Ka-band pulsed Doppler radar is simulated for the wake generated by a C-5A airlifter.

Mueller, E. R.

"APPLICATION OF UAV TECHNOLOGY TO EVALUATION OF TIME-BASED TRAJECTORY NAVIGATION REQUIREMENTS"

AIAA Paper No. 2004-6535, Chicago, IL, September 2004.

A review of air traffic control procedures and studies suggests that if airport capacity is to increase substantially it will be necessary to precisely control the flight paths and times of arrival of aircraft in the airport vicinity. One such method of achieving this precision, termed the individual flight corridor concept, is being studied to determine if such a process is feasible. The benefits of the concept, which have been evaluated by other researchers, are presented, and are followed by an analysis of the obstacles to and requirements for its implementation. Using this previous research as a foundation, the longitudinal and lateral navigation requirements are defined that implement the individual flight corridor concept with an equivalent level of safety to current arrival operations. The primary obstacle to meeting the navigation requirements of the time-based trajectory is uncertainty in the wind field forecast around the airport, so a simulation was designed to quantify the relationship between wind uncertainty, navigation errors, and aircraft dynamics. The results of the simulation suggest that wind errors up to 15 meters per second in either the longitudinal or lateral directions may be compensated for within the required navigation performance that will produce an equivalent level of safety to current operations, evidence that the individual flight corridor concept will be a viable method of increasing arrival capacity at some airports. An Unmanned Aerial Vehicle (UAV) currently under development at the Unmanned Flight Operations Laboratory of NASA Ames will be used to flight test the concept and validate the results of the simulation. Flight testing with a UAV is projected to reduce cost and increase safety relative to the use of manned aircraft, and provide more flexibility in the mix of equipment and guidance and control capabilities.

Muirhead, V. U.

"COMPRESSIBLE VORTEX FLOW"

AIAA Paper No. 1973-0106, Washington, DC, January 1973

The key role that the axial core flow plays in the characteristics of an unconfined compressible vortex has been examined. Isentropic compressible flow equations have been developed to relate pressure, density, and velocity. An index was developed to indicate the strength of a vortex produced by induced circulation and induced core flow. Using the index and the compressible flow equations, the variation of vortex characteristics with change in circulation, core velocity, atmospheric pressure, kinematic viscosity and the speed of sound was determined. The unconfined vortex was modeled with selected boundary conditions. Experimental observations are discussed and related to the theory.

Mula, S. M., Stephenson, J. H., Tinney, C. E. and Sirohi, J.

"DYNAMICAL CHARACTERISTICS OF THE TIP VORTEX FROM A FOUR-BLADED ROTOR IN HOVER"

Experimental Fluids, Vol. 54, 2013, pp.1600-1613.

Dynamical characteristics of tip vortices shed from a 1 m diameter, four-bladed rotor in hover are investigated using various aperiodicity correction techniques. Data are acquired by way of stereo-particle image velocimetry and comprises measurements up to 260 degrees vortex age with 10-degree offsets. The nominal operating condition of the rotor corresponds to $Re = 248,000$ and $M = 0.23$ at the blade tip. With the collective pitch set to 7.2 degrees and a rotor solidity of 0.147, blade loading (coefficient of thrust divided by rotor solidity) is estimated from blade element momentum theory to be 0.042. The findings reveal a noticeable, anisotropic, aperiodic vortex wandering pattern over all vortex ages measured. These findings agree with recent observations of a full-scale, four-bladed rotor in hover operating under realistic blade loading. The principal axis of wander is found to align itself perpendicular to the slipstream boundary. Likewise, tip vortices trailing from different blades show a wandering motion that is in phase instantaneously with respect to one another, in every direction and at every wake age in the measurement envelope.

Mula, S. M., Stephenson, S., Tinney, C. E. and Sirohi, J.

"DYNAMICAL AND EVOLUTIONARY CHARACTERISTICS OF THE TIP VORTEX FROM A FOUR-BLADED ROTOR IN HOVER"

68th AHS Annual Forum, May 2012, Fort Worth, TX.

The dynamical and evolutionary characteristics of the tip vortices produced by a reduced-scale, 1-m diameter, four-bladed rotor in hover are investigated using the well-known Q criterion combined with the center of mass approach. The data is acquired by way of stereo PIV and focused on wake ages up to 360 degrees with 10-degree offsets during hover conditions. The nominal operating condition of the rotor is at a rotational speed of 1520 RPM, corresponding to $Re = 248,000$ and a blade loading of 0.0446, obtained from BEMT estimates. Previous investigations revealed a noticeable, anisotropic, aperiodic vortex jitter pattern over all vortex ages which was not previously observed. Furthermore, the

core radius appeared to be constant after the first blade passage, even up to a vortex age of 260 degrees and was also not previously observed. These findings are confirmed using other vortex methods: Centroid of Vorticity and Normalized Helicity.

Muller, B.

"HIGH ORDER DIFFERENCE METHOD FOR LOW MACH NUMBER AEROACOUSTICS"

European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS 2001, Swansea, Wales, UK, September 2001

The Euler equations are split into a conservative and a symmetric non-conservative portion to allow the derivation of a generalized energy estimate. Owing to the large disparity of acoustic and stagnation quantities in low Mach number aeroacoustics, the split Euler equations are formulated in perturbation form. While the conventional central sixth-order accurate stencil is employed in the interior, the difference method is third-order accurate at the boundary to satisfy the summation by parts property analogous to the integration by parts in the continuous energy estimate. Since thereby a discrete energy estimate is automatically satisfied, strict stability of the high order difference method is guaranteed. The boundary conditions are implemented by a penalty term. The classical Runge-Kutta method is used for time integration. Spurious oscillations are suppressed by a new characteristic-based filter. The method has been applied to simulate vortex sound at low Mach numbers. The computed acoustic pressure generated by an almost circular Kirchhoff vortex is in excellent agreement with the analytical solution.

Muller, B.

"ON SOUND GENERATION BY THE KIRCHHOFF VORTEX"

Report 209/1998, 1998, Uppsala University Dept. of Scientific Computing, Uppsala, Sweden

A 2D test case for low Mach number computational aeroacoustics is provided. The Kirchhoff vortex is an elliptical patch of constant vorticity rotating with constant angular frequency in irrotational flow. This 2D flow field constitutes an exact solution of the 2D incompressible Euler equations. Due to its unsteadiness in the inertial frame of reference, the Kirchhoff vortex generates sound. Here, the exact incompressible velocity and pressure distributions and a low Mach number approximation of the far field acoustic pressure are stated. Moreover, the Helmholtz equation is exactly solved to yield the complete acoustic pressure field of an almost circular Kirchhoff vortex.

Muller, B. and Yee, H. C.

"ENTROPY SPLITTING FOR HIGH ORDER NUMERICAL SIMULATION OF VORTEX SOUND AT LOW MACH NUMBERS"

Journal of Scientific Computing, Vol. 17, No. 1-4, December 2002, pp. 181-190

Several recent developments in efficient, stable, highly parallelizable high order non-dissipative spatial schemes with characteristic based filters that exhibit low dissipation for long time linear and nonlinear wave propagations are utilized for computational aeroacoustics (CAA). For stability consideration, the Euler equations are split into a conservative and a symmetric non-conservative portion. Due to the large disparity of acoustic and stagnation quantities in low Mach number aeroacoustics, the split Euler equations are formulated in perturbation form to minimize numerical cancellation errors. Spurious oscillations are suppressed by a characteristic-based filter. The method has been applied to accurately simulate the sound emitted by an almost circular Kirchhoff vortex at low Mach numbers.

Muller, B. and Yee, H. C.

"HIGH ORDER NUMERICAL SIMULATION OF SOUND GENERATED BY THE KIRCHHOFF VORTEX"

Proceedings of 2nd AMIF Conference, 12-14 October 2000, pp. 1-14

An improved high order finite difference method for low Mach number computational aeroacoustics (CAA) is described. The improvements involve the conditioning of the Euler equations to minimize numerical cancellation errors, and the use of a stable non-dissipative sixth-order central spatial interior scheme and a third-order boundary scheme. Spurious high frequency oscillations are damped by a third-order characteristic-based filter. The objective of this paper is to apply these improvements in the simulation of sound generated by the Kirchhoff vortex.

Muller, E. A. and Obermeier, F.

"THE SPINNING VORTICES AS A SOURCE OF SOUND"

Conference Proceedings No. 22, September 1967, Specialists' Meeting of the Fluid Dynamics Panel of AGARD, Gottingen, Germany.

Flow and sound field of a simple aerodynamic sound source - the two-dimensional spinning vortices - are calculated. In this calculation the method of matched asymptotic expansions is employed. This method for the solution of singular perturbation problems has been developed during the last years. It allows for the computation of an asymptotic solution of the differential equations of the flow, which is valid both in the near field and the far field. One obtains a seventh power law in a characteristic velocity U for the sound power radiated by unit length of the spinning vortices in contrast to the eighth power law obtained by M. J. Lighthill for three-dimensional flows. It is possible to generalize the above method to vortex flows and their radiation fields; results will be given.

Muller, E.-A. and Obermeier, F.

"VORTEX SOUND"

Fluid Dynamics Research, Vol. 3, 1988, pp. 43-51.

Vortex motion is the only source of aerodynamic sound production in low Mach number flow: the unsteady part of the vorticity distribution contributes linearly to the sound field. The following fundamental model flows, which illustrate the vorticity as the predominant sound source in unsteady flows, are discussed: An initially planar elliptic vortex; two identical coaxial initially elliptic vortex rings, where a special case is the leap-frogging of two identical circular rings. For head-on collision of two identical circular vortex rings and for several cases of vortex-body interaction good agreement between theory and experiment exists. If the Mach number is not low, other mechanisms have also to be considered. Here the theory is not yet fully developed. Experimental results for a vortex-airfoil interaction in transonic flow show that local flow separation and boundary layer as well as compressibility effects play a basic role. However, if the motion of vorticity would be known in subsonic flow, essential parts of the sound field could be calculated by the theory. In addition, it is shown that the general theory is well suited to provide a better understanding of the scattering of sound waves by vortex motion, at least for long wave lengths.

Muller, R. H. G., Mba, M. N., Aymard, E., Favier, D., Berton, E. and Maresca, C.

"VISUALIZATION AND MEASUREMENT OF HELICOPTER ROTOR FLOW WITH SWEEPED BACK TIP SHAPES AT HOVER FLIGHT USING 'FLOW VISUALIZATION GUN' TIME LINE TECHNIQUE"

Experiments in Fluids, Vol. 21, Issue 3, July 1996, pp. 161-169.

The Flow Visualization Gun (FVG), a novel time line visualization technique, has been used to investigate the flow field of a helicopter rotor with swept back tip shape in hover flight condition. After introducing the FVG-technique, the paper presents some visualization photographs of the rotor blade tip vortices and the rotor downwash. Using orthogonal sets of flow photographs and digital image analysis, the 3-dimensional time line displacement within the flow and the tip vortex structure are determined. The data of 16 time-line experiments are interpolated in space and time to obtain velocity data on an evenly spaced 3-dimensional grid. Vorticity contour plots of the flow field show the complex arrangement of the tip vortices of the blade itself and of the preceding blade and some additional vorticity in the direct wake which may form a secondary vortex. Understanding and control of this vorticity distribution is important for the design of new efficient tip shapes. While the FVG technique has been used so far for qualitative investigation of complex flow patterns at local velocities of up to 20 m/s, a good comparison to laser velocimetry data validates the technique as an interesting tool for both qualitative and quantitative investigation.

Muller, S. D.

"BIO-INSPIRED OPTIMIZATION ALGORITHMS FOR ENGINEERING APPLICATIONS"

PhD Thesis, 2002, Swiss Federal Institute of Technology, Zurich, Switzerland.

The optimization of physical processes in engineering applications poses different challenges to the optimization engineer such as: Which optimization algorithm do I choose for a particular application? How do I choose optimization parameters and functions in a practical problem? How do I optimize

highly dynamical, noisy, or expensive problems? This thesis answers these questions in the context of stochastic optimization methods and applications. It provides new developments of bio-inspired optimization algorithms with an emphasis on evolutionary algorithms and their applications to a wide range of problems in the areas of turbomachinery, aeronautics, and micro- and nanotechnology. The development of bio-inspired algorithms includes the coupling of evolutionary algorithms with machine learning techniques for generalization purposes, the enhancement of convergence speed of evolutionary algorithms for parallel computer architectures, and a novel optimization algorithm inspired by the food-searching behavior of bacteria. In the application part, we discuss the optimal design of airfoil profiles, the cooling of turbine blades, jet mixing, and aircraft trailing vortex destruction, as well as micromixers, design of microchannels, and molecular dynamics applications.

Muller, Y.-A., Aubrun, S. and Masson, C.

"DETERMINATION OF REAL-TIME PREDICTORS OF THE WIND TURBINE WAKE MEANDERING"

Experimental Fluids, Vol. 56, 2015, pp. 56-1 - 56-11.

The present work proposes an experimental methodology to characterize the unsteady properties of a wind turbine wake, called meandering, and particularly its ability to follow the large-scale motions induced by large turbulent eddies contained in the approach flow. The measurements were made in an atmospheric boundary layer wind tunnel. The wind turbine model is based on the actuator disc concept. One part of the work has been dedicated to the development of a methodology for horizontal wake tracking by means of a transverse hot wire rake, whose dynamic response is adequate for spectral analysis. Spectral coherence analysis shows that the horizontal position of the wake correlates well with the upstream transverse velocity, especially for wavelength larger than three times the diameter of the disc but less so for smaller scales. Therefore, it is concluded that the wake is a rather passive tracer of the large surrounding turbulent structures. The influence of the rotor size and downstream distance on the wake meandering is studied. The fluctuations of the lateral force and the yawing torque affecting the wind turbine model are also measured and correlated with the wake meandering. Two approach flow configurations are then tested: an undisturbed incoming flow (modelled atmospheric boundary layer) and a disturbed incoming flow, with a wind turbine model located upstream. Results showed that the meandering process is amplified by the presence of the upstream wake. It is shown that the coherence between the lateral force fluctuations and the horizontal wake position is significant up to length scales larger than twice the wind turbine model diameter. This leads to the conclusion that the lateral force is a better candidate than the upstream transverse velocity to predict in real time the meandering process, for either undisturbed (wake free) or disturbed incoming atmospheric flows.

Mullins, J.

"TRAILS OF DESTRUCTION"

New Scientist, Vol. 152, No. 2056, November 1996, pp. 28-31

The horizontal and violently spinning streams of air, called wake vortices, which trail behind large aircrafts are hazardous for the following aircrafts. The ferocious nature of wake vortices necessitates adequate spacing between aircrafts to avoid plane crashes. Aircraft designers and air traffic controllers focus their attention on understanding the formation, persistence, decay, and prediction of vortices. Understanding the influence of wing design and weather conditions on vortex formation are important for overcoming the problems posed by wake vortices.

Mundra, A. D., Cooper, Jr., W. W., Smith, A. P., Audenaerd, L. F. and Lunsford, C. R.

"POTENTIAL BENEFITS OF A PAIRED APPROACH PROCEDURE TO CLOSELY SPACED PARALLEL RUNWAYS IN INSTRUMENT AND MARGINAL VISUAL CONDITIONS"

27th Digital Avionics Systems Conf., October 2008, St. Paul, Minnesota

This paper discusses a concept called 'Paired Approaches' which is designed to facilitate approaches to closely spaced parallel runways (CSPRs) -- i.e., runways separated by 700 feet to 2500 feet, in instrument meteorological conditions (IMC). This paper focuses on the potential benefits of the procedure. It first provides a brief review of the procedure and prior work. It discusses the variety of procedures currently available for parallel runways, and discusses the magnitude of the delay problem in the National Airspace System (NAS) not addressed by any of these existing procedures or procedures under development, but which the proposed paired approach procedure would address. It presents the potential capacity gain from the paired approach procedure at two representative major airports, and the percentage of time that the procedure could be available. The paper also presents a summary of potential infrastructure requirements for implementing the procedure, and concludes by providing an outline of the research and development needed to establish its deployment in the NAS.

Munk, M. M.

"NOTE ON VORTICES ON THEIR RELATION TO THE LIFT OF AIRFOILS"

NACA TN-184, March 1924, NACA Langley Aero. Lab., Langley Field, VA

This note, prepared for the NACA, contains a discussion of the meaning of vortices, so often mentioned in connection with the creation of lift by wings. The action of wings can be more easily understood without the use of vortices.

Munk, M. M.

"NOTE ON VORTICES AND ON THEIR RELATION TO THE LIFT OF AIRFOILS"

Technical Note No. 184, March 1924, National Advisory Committee for Aeronautics, Washington, DC

This note, prepared for the N. A. C. A., contains a discussion of the meaning of vortices, so often mentioned in connection with the creation of lift by wings. The action of wings can be more easily understood without the use of vortices.

Munster, C. and Schwarz, C.

"AUSWERTUNG VON WIRBELSCHLEPPENMELDUNGEN IM US AVIATION SAFETY REPORTING SYSTEM (ASRS)"

Report: IB 111-2010/33, DLR, German Aerospace Research Center, July 2010, Cologne, Germany.

An evaluation of the NASA Aviation Safety Reporting System (ASRS) database was attempted. The database listed 488 reported wake encounters and 58 incidents (physical or personal damage) between the years of 1999 and 2009, of which most occurred during approach and landing. Most of the encountering aircraft were medium sized behind a medium or heavy aircraft.

Murayama, M. and Nakahashi, K.

"NUMERICAL SIMULATION OF VORTICAL FLOWS USING VORTICITY CONFINEMENT COUPLED WITH UNSTRUCTURED GRID"

AIAA Paper No. 2001-0606, Reno, NV, January 2001

This paper discusses the use of the vorticity confinement method coupled with the unstructured grid approach to simulate vortical flows. The method is evaluated by several vortical flow computations of the leading-edge separation vortices on delta wings and the wing tip vortices of NACA0012 wing. It is shown that the vorticity confinement can keep the vorticity away from the numerical diffusion effectively. Although further study to reduce the dependency of the confinement coefficient on the grid density is required, the present results indicate the possibility of accurate vortical flow computations by the vorticity confinement method coupled with unstructured and adaptive refinement grids.

Murman, E. M. and Stremel, P. M.

"A VORTEX WAKE CAPTURING METHOD FOR POTENTIAL FLOW CALCULATIONS"

AIAA Paper No. 1982-0947, St. Louis, MO, June 1982

A method is presented for modifying finite difference solutions of the potential equation to include the calculation of non-planar vortex wake features. The approach is an adaptation of Baker's 'cloud in cell' algorithm developed for the stream function-vorticity equations. The vortex wake is tracked in a Lagrangian frame of reference as a group of discrete vortex filaments. These are distributed to the Eulerian mesh system on which the velocity is calculated by a finite difference solution of the potential equation. An artificial viscosity introduced by the finite difference equations removes the singular

nature of the vortex filaments. Computed examples are given for the two-dimensional time dependent roll-up of vortex wakes generated by wings with different spanwise loading distributions.

Mursch-Radlgruber, E., Bradley, S. and von Hunerbein, S.

"VORTEX DETECTION AND RANGING (VODAR)"

ISARS 2004, Cambridge, UK, July 2004

Case studies of wing-tip vortices from landing aircraft have previously been reported from a linear array of four SODARs that recorded only vertical velocities. Aircraft vortex structure is clear on the single-shot SODAR profiles. We develop a relatively simple potential flow vortex model, which includes the essential features of the aircraft and of the SODAR array, allowing visualization of the time evolution of the 3D vortex structure. Comparison between field results and the simple vortex model demonstrates the prospect of routinely monitoring wakes and developing of climatology of their interaction with the environment.

Murtaza, A., Parvez, K., Shahid, H. and Mehmood, Y.

"DESIGN AND COMPUTATIONAL FLUID DYNAMIC ANALYSIS OF SPIROID WINGLET TO STUDY ITS EFFECTS ON AIRCRAFT PERFORMANCE"

International Research Journal of Engineering and Technology, Vol. 4, Issue 12, December 2017, pp. 1298-1306.

In aerodynamic applications usual demands are reduction in overall drag and increase in lift. This constitutes a major challenge in any aerodynamic application or study. The same is true for a typical aircraft application. The drag profile of most aircrafts has a major portion of its drag consisting of lift induced drag. This drag can be reduced by using wingtip devices such as winglets etc. One such winglet is bio-inspired and is known as spiroid winglet. Present study deals with the investigation of the effects of spiroid winglets geometric modifications on aerodynamic performance of aircraft. The study consists of modifying the design of existing spiroid winglet based on paper and carrying out numerical simulations using Computational Fluid Dynamic (CFD) methods to simulate a modified spiroid winglet design consisting of a 360 degree blended wingtip and having enhanced aerodynamic performance.

Murugan, T. and Das, D.

"ON EVOLUTION AND ACOUSTIC CHARACTERISTICS OF A COMPRESSIBLE VORTEX RING"

Aeroacoustics, Vol. 7, No. 3 & 4, 2008, pp. 199-222.

Sound generated during formation of a compressible vortex ring at the open end of a shock tube and during its propagation is studied experimentally for shock Mach numbers of 1.28 to 1.61. The occurrence of different events such as primary ring formation, growth of the primary ring, secondary

and tertiary vortices formation, and pinching-off are identified as predominant noise producing events. Wavelet analysis of the measured microphone signal identifies the time of occurrence of the above events which is verified using flow visualization pictures. The distributions of acoustic fluctuations are measured at a fixed distance from the exit center of the tube at different angular locations in horizontal diametrical plane and the directivity of the amplitude of sound pressure associated with the evolution of vortex ring is found. It is observed that the vortex ring's evolution sound is dominant between 25 to 50 degrees angle from the axis of the shock tube. Experiments with short driver section produce rings with small trailing jet. Sound generated during the initial formation of these rings, after the diffraction of the incident shock at the open end of the shock tube, is dominant than the vortex ring's evolution sound. In shock tubes with larger driver section, the primary vortex ring is followed by a relatively longer trailing jet. In these cases, sound generated during formation of subsequent shear-layer vortices and their interaction with the trailing jet is also significant.

Mutuel, L.

"INSTRUMENTATION SYSTEM FOR ONBOARD DETECTION, WARNING AND AVOIDANCE OF WAKE VORTEX, WINDSHEAR AND CLEAR AIR TURBULENCE HAZARDS - FIRST RESULTS FROM I-WAKE TEST CAMPAIGNS"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

The European funded I-WAKE project is dedicated to the functional definition of a future Detection, Warning and Avoidance system for atmospheric hazards, the assessment of proper Human-Machine Interface (HMI), the demonstration of airborne detection of wake vortices and the development of laser technology for a future affordable system. One of the system requirements is its operation in all phases of flight and in all weather; to satisfy this request, the system must be multi-sensor, e.g. a combination of lidar, radar and uplinked data, and must compensate the 2.4km detection range of its lidar with a predictor. Early June, the project completed its flight simulator phase to assess with pilots HMI solutions for wake vortex hazard display on Navigation Display, Vertical Navigation Display and Primary Flight Display. For wake vortices, the predictor used is based on VFS degraded by the uncertainties on the model inputs. The flight simulator tests were conducted at AIRBUS facilities in Hamburg on the THOR simulator. The impact of weather on the wake prediction was compared in a robustness analysis to the other input parameters. End of June, the flight tests were successfully carried out in Toulouse to show the feasibility of airborne detection of wake vortices. The equipment was installed onboard the NLR Cessna Citation II test aircraft and detected invisible wake vortices generated by an A340-600 flying 2-3Nm ahead. Thanks to varied atmospheric conditions, how much weather impacts the lidar detection performance can be studied. The presentation will summarize the results of the wake predictor robustness analysis with respect to parameter uncertainties and present for the first time the successful results of the June flight test campaign. Recommendations for the system definition conclude the talk.

Mutuel, L. and Baillon, B.

"SYSTEM AND METHOD FOR DETECTING WAKE TURBULENCE OF AN AIRCRAFT"

US Patent 8,478,459 B2, July 2013

System for detecting wake turbulence of a first aircraft, which can be embedded onboard a second aircraft, comprising: first means for determining the roll of the second aircraft; second determination means of an envelope of reference roll curves which is representative of a wake turbulence created by the first aircraft; means for comparing, over a sliding window, the roll of the second aircraft and the envelope of reference roll curves; and alarm means for forewarning the pilot of the second aircraft of the detection of wake turbulence of the first aircraft when the said comparison is below a resemblance threshold.

Mutuel, L. H., Barbaresco, F., Juge, P., Klein, M., Canal, D., Ricci, Y., Schneider, J.-Y., Moneuse, J.-F. and Lavergne, E.

"ATM DECISION SUPPORT TOOL FOR WAKE VORTEX HAZARD MANAGEMENT COMBINING SENSORS AND MODELING"

AIAA Paper 2014-2332, June 2014, Atlanta, GA.

Capacity gains in the terminal area and on the airport surface can be achieved by integrating wake vortex hazard management more dynamically in the setting of separation minima. To define these more efficient intervals, smart planning techniques are integrated into a wake vortex decision support system. The system performs prediction, detection and monitoring of wake vortices based on wake vortex sensor suite and sensor simulations, wake predictor, weather sensors and weather nowcasting and forecasting. The architecture and system performance has been verified and validated during several trials. The results and recommendations have been used to define the trials to come and subsequent technology improvements.

Myers, T. J.

"DETERMINATION OF BRAGG SCATTER IN AN AIRCRAFT GENERATED WAKE VORTEX SYSTEM FOR RADAR DETECTION"

Ph.D. Thesis, August 1997, Virginia Polytechnic Institute, Department of Electrical Engineering, Blacksburg, VA

Remote detection and tracking of wingtip generated wake vortices is important for hazard avoidance especially near airports. Aircraft that fly through these hazardous vortices experience sudden induced roll. Experiments have demonstrated that there is sufficient radar cross section for remote detection at frequencies ranging from VHF to C band (100 MHz to 5 GHz). The mechanism that yields this radar cross section is Bragg scattering from the index of refraction variations due to the atmospheric water vapor and potential temperature fields being mixed by the wake vortex system. Refractive index variations of the size that correspond to half the operating radar wavelength produce the observed radar return. Previous analysis has postulated turbulence within the wake vortex to be the generator

of the index of refraction variations. In this work, a new mechanism is identified that does not assume turbulence within the wake vortex system. This 'laminar flow mechanism' causes refractive index structuring that stretches into successively smaller spirals over time as the wake vortex system swirls and descends through the stratified atmosphere. The results are quantitatively consistent with experimental data. Results indicate that this new mechanism has a sharply peaked doppler spectrum which is encouraging for coherent detection by doppler radar.

Myers, T. J., Scales, W. A. and Marshall, R. E.

"DETERMINATION OF AIRCRAFT WAKE VORTEX RADAR CROSS SECTION DUE TO COHERENT BRAGG SCATTER FROM MIXED ATMOSPHERIC WATER VAPOR"

Radio Science, Vol. 34, No. 1, January-February 1999, pp. 103-111

Remote detection and tracking of wing-tip generated wake vortices are important for hazard avoidance, especially near airports. Aircraft that fly through these hazardous vortices experience sudden induced roll. Experiments have demonstrated that there is sufficient radar cross section for remote detection at frequencies ranging from VHF to C band (100 MHz to 5 GHz). The mechanism that yields this radar cross section is Bragg scattering from the index of refraction variations due to the atmospheric water vapor being mixed by the wake vortex system. Refractive index variations of the size that correspond to half the operating radar wavelength produce the observed radar return. Previous analysis has postulated turbulence within the wake vortex to be the generator of the index of refraction variations. In this work, a new mechanism is identified that does not assume turbulence within the wake vortex system. This 'laminar flow mechanism' mixes the stratified atmosphere as the wake vortex system swirls and descends, which causes refractive index structure that stretches into successively smaller spirals over time. The results are quantitatively consistent with experimental data.

Myose, R. Y. and Blackwelder, R. F.

"AN EXPERIMENTAL STUDY OF THE INTERACTION OF LARGE THREE-DIMENSIONAL EDDIES AND SMALL STREAMWISE VORTICES"

AIAA Paper No. 1997-0442, Reno, NV, January 1997

The interactive effect of large three-dimensional eddies convecting above small near wall streamwise vortices was experimentally studied. Counter-rotating streamwise vortices emulating turbulent boundary layer near wall structure were generated by a Gortler instability mechanism. Large outer region eddies were generated and shed three-dimensionally by pitch oscillating a NACA 0009 airfoil with saw-tooth shape trailing edge extension. The structure of these large three-dimensional eddies included a high speed insweep toward the wall whose leading-edge front was skewed in the spanwise direction. The near wall streamwise vortices broke down when this high-speed front arrived overhead. This suggests that the large outer region eddies, and particularly the high speed insweep, plays a role in the bursting process of turbulent boundary layers.

Nagati, M. G., Iversen, J. D. and Vogel, J. M.

"VORTEX SHEET MODELING WITH CURVED HIGHER-ORDER PANELS"

J. Aircraft, Vol. 24, No. 11, November 1987, pp. 776-782

A method is presented for predicting the geometry of a vortex sheet trailing a lift-generating wing. It differs from other methods in that it uses a continuous vorticity distribution and curved panels rather than discrete vortex filaments or flat panels. Although the original intent was to apply cyclic iterations to the computed results, it was found that the results of the initial cycle were already in good agreement with the experiment.

Nagid, G.

"WAKE TURBULENCE - THE INVISIBLE ENEMY"

ICAO Bulletin, Vol. 43, April 1988, pp. 14-15

Studies to reduce the danger of wake turbulence, especially to following aircraft, and guidelines for wake turbulence classification of aircraft are discussed. An ICAO conference created three categories of aircraft based on maximum certified take-off mass, with heavy craft being those over 136,000 kg, light craft being less than 7,000 kg and medium craft being those in between. The radar separation minima for light aircraft following medium aircraft has been increased from 7.4 km to 9.3 km. Further guidance material is being developed based on wake turbulence research.

Nagid, G.

"ICAO WAKE TURBULENCE PROVISIONS"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 10-1 - 10-12.

The ICAO wake turbulence provisions have been implemented by most of the Contracting States. Considerable efforts have been made by ICAO to standardize these provisions world-wide. Nevertheless, some States, including the US and UK, still have provisions which are different from those of ICAO in terms of designation and number of wake turbulence aircraft categories. Additional research and development programs, to detect and track wake vortices with a view to determining their dynamics and decay mechanism, are essential to determine the feasibility of reduced separation between aircraft, which would alleviate congestion and reduce delays at major airports.

Naguib, A. M. and Koochesfahani, M. M.

"ON WALL-PRESSURE SOURCES ASSOCIATED WITH THE UNSTEADY SEPARATION IN A VORTEX-RING/WALL INTERACTION"

Physics of Fluids, Vol. 16, No. 7, July 2004, pp. 2613-2622

Molecular tagging velocimetry measurements from an earlier investigation are used to study the wall-pressure and the flow structures responsible for its generation in the flow field resulting from the impingement of an axisymmetric vortex ring on a flat wall. The velocity-field data are used to obtain the spatial distribution of the pressure sources, and the result is employed in conjunction with the solution to Poisson's equation to yield the wall-pressure information. The outcome reveals a characteristic wall-pressure signature that is produced repeatedly whenever the primary vortex ring interacts with the wall to form vortex rings with opposite sense of vorticity. The details of the signature are analyzed and related to specific flow features and their mutual interaction at different phases of the generation/evolution cycle of the new rings. Finally, the flow mechanisms leading to the generation of substantial positive and negative wall pressure in the characteristic signature are clarified.

Naiman, A. D., Lele, S. K. and Jacobson, M. Z.

"LARGE EDDY SIMULATIONS OF PERSISTENT AIRCRAFT CONTRAILS"

AIAA Paper No. 2011-0993, January 2010, Orlando, FL.

A three-dimensional large eddy simulation (LES) model has been used to study the development of persistent aircraft condensation trails (contrails) under a variety of atmospheric and initial conditions. The LES solves the incompressible Navier-Stokes equations with a Boussinesq approximation for buoyancy forces. Contrail ice particles are modeled using a Lagrangian tracking approach, with water mass and heat exchange coupled between the vapor and solid phases. Three sets of simulations vary the atmospheric turbulence environment, initial aircraft wake flow field, and ambient humidity to investigate the sensitivity of contrail properties to these parameters. Higher levels of turbulence and vertical shear, larger aircraft, and higher ambient humidity are all found to increase the ice mass present in the contrail to some extent. Each of these parameters also affects the optical properties and area coverage of the resulting contrail. These simulations provide sensitivity data that are used to improve a model of aircraft exhaust plume dynamics implemented in a global scale climate model.

Nakagawa, T.

"ON UNSTEADY AIRFOIL-VORTEX INTERACTION"

Acta Mechanica, Vol. 75, 1988, pp. 1-13.

An experimental investigation on unsteady airfoil-vortex interaction has been done. The incident vortex, to interact with a downstream airfoil (NACA 0018, chord length 20 mm), is generated by a square cylinder (side length $D=20$ mm). The square cylinder and airfoil are arranged in tandem and the spacing ratio L/D of the central distance to the side length is set a constant value of 4.625. The free stream Mach numbers are varied between 0.153 and 0.750, whereas the free stream Reynolds numbers (based on the side length D) are varied between 71300 and 344000. It is found that as the incident vortex approaches the airfoil, the circulation and scale are decreased until it arrives at a position near the leading edge of the airfoil. During this stage, some circulation of the incident vortex is

transferred to the secondary vortex generated on the airfoil opposite to the surface that the incident vortex approaches. Thus, circulation and scale of the secondary vortex is increased. However, after the incident vortex goes further downstream, no circulation of the incident vortex is transferred to the secondary vortex effectively. As the result, both the incident vortex and secondary vortex decay due to the viscous dissipation through the interaction with the boundary layer of the airfoil. The locus of the incident vortex is deviated in such a way that it goes away from the airfoil. The streamwise position of the secondary vortex is adjusted by the incident vortex, or vice versa, to meet each other just behind the trailing edge of the airfoil.

Nakamura, Y. and Uchida, S.

"BREAKDOWN CONDITION OF AN AXISYMMETRIC SWIRLING FLOW"

AIAA Journal, Vol. 19, No. 8, August 1981, pp. 1083-1085

A method for prediction and explanation of vortex breakdown using a simple axial velocity profile is proposed. The principle underlying the method is to find solutions which approximately satisfy the Navier-Stokes equations, thus leading to the critical condition of breakdown.

Nakazono, Y.

"FLOW STRUCTURE OF ANNULAR JETS AND EFFECT OF ACOUSTIC EXCITATION ON THEIR MIXING"

AIAA-Paper No. 1996-0640, Reno, NV, January 1996

The effect of inner-to-outer nozzle diameter ratio on the flow structure of the wake and jets vortex speed have been studied by using a flow visualization method and a conditional sampling technique. As a result, convection velocity of wake vortex is faster than that of jet vortex. When inner-to-outer nozzle diameter is small, the wake has a helical mode. But, for large inner-to-outer diameter ratio, this mode changes, and large energetic wake vortex is generated periodically and moves downstream. Next, the effects of sound wave on their mixing were studied. Sound waves related to the shear layer were mainly selected. Mean velocity, fluctuation velocity and its spectra were measured, and jet flow was investigated by using a Schlieren photography and a smoke wire method.

Nangia, R. K. and Palmer, M. E.

"FORMATION FLYING OF COMMERCIAL AIRCRAFT - ASSESSMENT USING A NEW APPROACH - WING SPAN LOAD & CAMBER CONTROL"

AIAA Paper No. 2007-250, Reno, NV, January 2007

The idea of flying commercial aircraft in formation to reduce fuel usage, has been around for some time. There are many results available using idealized approaches e.g. vortex lattice formulations. In view of the greater importance being attached to environmental aspects, the need has arisen to evaluate the possible advantages and disadvantages. This paper steps up the analysis level exploiting a

recently developed design method that allows span loading and camber control on wings with without winglets. The method has been adapted to assess the aerodynamics of wings in formation and then to redesign them to eliminate induced roll effects. From a limited number of flight formation configurations assessed so far, the method predicts induced drag reductions of near 30%, affording overall drag reductions of the order of 15%. The benefits may well be larger, using other formation spacing parameters. Limited results using an Euler solver reflect benefits of the same order.

Narain, J. P. and Uberoi, M. S.

"THE MOTION OF A TRAILING VORTEX-WAKE IN A STRATIFIED MEDIUM"

Atmospheric Environment, Vol. 8, No. 5, May 1974, pp. 459-473

An analytical study of a trailing vortex-wake in a uniform and a stratified environment is presented. A turbulent entrainment velocity is postulated based on the assumption of similarity of the wake surface and consistent with several averaged conservation equations. In a homogenous density environment, the descending wake is brought to rest due to its buoyancy in the initial phase of wake motion. It is then accelerated upwards. The lifetimes of the wakes are found to be in excellent agreement with previous experimental results. In the absence of mutual interaction of vortices in the wake, the final ascending phase is a decelerating phase. The effect of weak linear stratification is to damp the movement of the vortex wake. The wake oscillates with decreasing amplitude and wavelengths with increasing magnitudes of linear stratification.

Narain, J. P. and Uberoi, M. S.

"TRAILING VORTEX-PAIR INSTABILITY"

Phys. Fluids, Vol. 16, No. 6, June 1973, pp. 761-768

The instability of a vortex-pair to infinitesimal disturbances is studied in the inviscid and incompressible fluid approximations. The cores of the vortices contain uniform axial-velocity jets of fluid density different from that of the surrounding medium. In one model a nonrotating core with surrounding potential vortex is assumed, and in the other a uniformly rotating core. In the lowest order of a perturbation parameter, denoting the ratio of vortex core radius to the distance between the vortices, the long-wavelength symmetric amplification factor of a vortex-pair decreases with increasing jet axial-velocity in either model, with decreasing core density in a rotating core model, and with increasing core density in nonrotating core model. The vortex-pair is more unstable to negative mode of deformation than to the positive mode in the presence of an axial jet in both models considered. The surface tension has a destabilizing effect on the vortex pair in the long-wavelength approximations. The effect of core density and jet axial velocity on long-wavelength symmetric amplification factors of the vortex pair in higher orders of perturbation parameters have also been outlined.

Narain, J. P. and Uberoi, M. S.

"NONLINEAR STABILITY OF CYLINDRICAL VORTEX ENCLOSING A CENTRAL JET OF LIGHT OR DENSE FLUID"

Phys. Fluids, Vol. 16, No. 9, September 1973, pp. 1406-1417

A nonlinear analysis of the inviscid stability of a cylindrical vortex enclosing a central jet of light or dense fluid is presented. A uniformly valid second-order expansion is obtained using the method of multiple time scales. For a stagnant core surrounded by a potential vortex, the axisymmetric mode remains stable to various scales of disturbances independent of core density. For asymmetric modes, the nonlinear effects make the stagnant core vortex sheet more unstable in second order for a given value of the core density. A central jet of any finite density always has a destabilizing effect on the jet-vortex system undergoing any mode of deformation. A jet of any velocity tends to increase the unstable growth rates with increasing order of perturbations. The surface tension has a stabilizing effect with increasing order of perturbations. The frequency of oscillation becomes amplitude dependent in various orders of perturbations. The cylindrical surface departs significantly from its initially perturbed sinusoidal form and assumes a sinusoidal form.

Narducci, R.

"COMPARISON OF BLADE TIP VORTEX CALCULATIONS TO WIND TUNNEL MEASUREMENTS"

Proceedings of the ARO Rotorcraft Wake Prediction Basic Research Workshop, March 2009, Georgia Institute of Technology, Atlanta, GA, p. 185.

Accurate calculations of blade tip vortices by computational fluid dynamics methods is of ever-increasing importance to the rotorcraft community. Increasing demand for rotor performance requires design and evaluation of rotor systems with high-fidelity methods for helicopter manufacturers to remain competitive. Generally, CFD can provide accurate near-field solutions that capture key physical elements since they are based on first principles. However, CFD methods are notorious for premature dissipation when it comes to far field wakes. The implication is that in the rotor environment blade tip vortices are weakened or washed out completely prior to the arrival of the proceeding blade. The result is improper prediction of blade loads on the outboard section and ultimately poor rotor performance prediction. Calculations are made on a stationary rotor blade in Mach 0.15 flow for the purpose of benchmarking the ability of steady Reynolds Average Navier Stokes methods to compute blade tip vortices. Several spatial discretization schemes and gridding strategies are investigated. Computed results are compared against measurements made by the quantitative wake survey system in the Boeing-Vertol Wind Tunnel.

Nash, J. F.

"SOME CALCULATIONS EXTENDING THE WILLIAMS' MODEL OF THE DECAY OF TRAILING VORTICES"

LG73ER0191, October 1973, Lockheed-Georgia Company, Marietta, GA

Part I gives the results of calculations presented for any given span load distribution, relevant to the 'second stage' of trailing-vortex decay (where roll-up is complete but before the interaction between the two vortices becomes dominant). The problem of relating equivalent wake 'age' to distance downstream of the wing is addressed, for the case of a turbulent vortex. It is shown that a variable eddy viscosity is physically more realistic than a constant one, and the decay of the vortices with distance is calculated on this basis, for three simple spanwise-loading distributions. Some exploratory calculations have been performed to investigate the influence on vortex decay of the displacement effect associated with core injection. It is shown that the main effect is to limit the maximum circumferential velocities, present in the vortex, during the early phases of decay. In Part II, the vorticity equations, expressed in cylindrical polar coordinates, are solved for a semi-infinite rotationally-symmetric viscous vortex, in an incompressible, non-uniform axial flow. An advanced implicit numerical scheme is used, based on the extended Choleski method. The scheme is unconditionally stable, resulting in an economical, highly efficient computation tool. Input to the calculations consists of the vector vorticity profiles, at some initial axial station, together with the longitudinal variation of the far-field axial velocity. Output consists of the vector vorticity and velocity profiles at successive stations downstream.

Nathan, N. D. and Green, R. B.

"THE FLOW AROUND A MODEL HELICOPTER MAIN ROTOR IN GROUND EFFECT"

Experimental Fluids, Vol. 52, 2012, pp. 151-166.

Wind tunnel measurements of the wake below and ahead of a model helicopter main rotor in simulated forward flight in ground effect are presented. The wind tunnel used was equipped with a rolling road, and the ground speed was matched to the wind tunnel speed for a representative simulation in the wind tunnel of forward flight over the ground. Particle image velocimetry was used to investigate the structure of the wake, and it was observed that the moving ground had a remarkable effect on the flow; the wake is closer to the rotor and its size is reduced compared with the stationary ground case. The detailed distribution of vorticity within the wake is affected by the moving ground, and the mechanism for this is discussed in the paper.

Nathan, N. D. and Green, R. B.

"FLOW VISUALISATION OF THE HELICOPTER BROWN-OUT PHENOMENON"

The Aeronautical Journal, Vol. 113, No. 1145, July 2009, pp. 467-478.

Quantitative and qualitative results of a series of experiments conducted on a rotor in ground effect at low forward speeds are presented. The velocity over a wide area of the ground effect wake was measured using particle image velocimetry, and the evolution of the flow is described as the forward speed increases. The formation of a dust cloud leading to so-called helicopter brown-out was simulated through a series of flow visualization experiments. The technique involved sprinkling a fine dust on the ground below and ahead of the rotor. Larger dust clouds were observed at lower forward

speed, and the dust cloud penetrated the areas of the flow including those where vorticity levels were of low magnitude and occasional velocity fluctuations from the mean were large.

Naughton, J. W. and Settles, G. S.

"EXPERIMENTS ON THE ENHANCEMENT OF COMPRESSIBLE MIXING VIA STREAMWISE VORTICITY, PART I -- OPTICAL MEASUREMENTS"

AIAA Paper No. 1992-3549, July 1992, Nashville, TN.

In recent years, compressible turbulent mixing flows have been studied in detail to understand and control the physics governing them. Although much has been learned from these studies, attempts to significantly increase the mixing of two streams have been largely unsuccessful. Based upon promising results in subsonic flow, the present study was initiated to increase the compressible mixing rate of a supersonic jet injected into a co-flowing supersonic stream by adding streamwise vorticity to the injected flow. This flowfield was imaged using the Planar Laser Scattering (PLS) technique, and mixing rates were derived entirely from captured images. The results of this image analysis indicate that increases in mixing rate of up to 60 percent are possible through the addition of streamwise vorticity. Furthermore, the degree of mixing enhancement appears to be dependent on the amount of swirl added. Analysis of the instantaneous turbulent structure suggests that this increase in mixing is due to a modification of the largest turbulent structures in the mixing layers.

Naughton, J. W. and Settles, G. S.

"A THEORETICAL FRAMEWORK FOR MIXING LAYERS SURROUNDING COMPRESSIBLE TURBULENT SWIRLING JETS"

AIAA Paper No. 94-2245, June 1994, Colorado Springs, CO.

Recently, there has been some success in increasing the growth rates of compressible jets by adding swirl to the flow. Although some explanations for this phenomenon have been proposed, no definitive theory has been presented. In this paper, a framework for analyzing these flows is developed, and its results are compared with experimental data. The results indicate that the theoretical model can predict the enhanced growth rates associated with compressible swirling jets relative to their nonswirling counterparts. Furthermore, a convective Mach number for these swirling flows is discussed. Including compressibility effects determined by this parameter in the current analysis shows that there is an optimal amount of swirl that maximizes the mixing enhancement. Thereafter, any additional swirl actually decreases the enhancement effect.

Naughton, J. W., Cattafesta III, L. N. and Settles, G. S.

"AN EXPERIMENTAL STUDY OF COMPRESSIBLE TURBULENT MIXING ENHANCEMENT IN SWIRLING JETS"

Journal of Fluid Mechanics, Vol. 330, 1997, pp. 271-305.

Compressible jets with various amounts of swirl and compressibility are investigated experimentally. The mixing-layer growth rate is obtained from time-averaged images of the mixing layer using the planar laser scattering (PLS) technique, and the swirl is quantified with laser Doppler velocimetry and intrusive probes. The results conclusively demonstrate that the addition of swirl to the jet increases entrainment by up to 60 percent compared to a corresponding non-swirling case. Instantaneous PLS images reveal modified turbulent structure in the mixing layer of the swirling-jet cases. In particular, analysis of these images indicates that both the spatial extent and amplitude of the largest turbulent fluctuations are increased when swirl is added. Based on these results, a parameter B that correlates the observed growth-rate enhancement is proposed. This parameter is derived assuming that the streamwise vorticity, generated in the mixing layer by the addition of small amounts of swirl, causes additional turbulent mixing that increases the growth rate. When the available growth-rate data for swirling jets are plotted against this parameter, they collapse to a single curve with increased enhancement for higher values of B. This result implies that the degree of enhancement increases with compressibility, although the dimensional growth rates for the present compressible swirling-jet cases are still less than those of their incompressible counterparts.

Naughton, J. W., Cattafesta, L. N. and Settles, G. S.

"EXPERIMENTS ON THE ENHANCEMENT OF COMPRESSIBLE MIXING VIA STREAMWISE VORTICITY, PART II -- VORTEX STRENGTH ASSESSMENT AND SEED PARTICLE DYNAMICS"

AIAA Paper No. 1993-0742, January 1993, Reno, NV.

In recent years, compressible turbulent mixing has been studied in detail to understand and control the physics governing it. Although much has been learned from these studies, attempts to significantly increase the mixing of two streams have been largely unsuccessful. Based on promising results in subsonic flow, the present study was initiated to increase the mixing of co-flowing supersonic streams by way of streamwise vorticity. Part I of this study measured the mixing-layer growth rates of these swirling flows using Planar Laser Scattering (PLS). In this second part of the study, the strengths of the vortices are quantified using intrusive probes and Laser Doppler Velocimetry (LDV). In addition, the seed particles used for the PLS imaging are measured with a two-color light-transmission technique. An analysis of these experimental results indicates that the particles faithfully represent the dynamics of the turbulent swirling flow. Comparing the previously-determined mixing-layer growth rates with the present vortex strength data reveals that the increase of turbulent mixing, up to 60 percent for the cases studied, scales with the degree of swirl. Furthermore, this mixing enhancement appears to be independent of the level of compressibility of the mixing layer.

Naumov, I. V., Mikkelsen, R. F., Okulov, V. L. and Sorensen, J. N.

"PIV AND LDA MEASUREMENTS OF THE WAKE BEHIND A WIND TURBINE MODEL"

The Science of Making Torque from Wind, published in IOP Journal of Physics: Conference Series, Vol. 524, 2014, pp. 012168-1 to 012168-10.

In the present work we review the results of a series of measurements of the flow behind a model scale of a horizontal axis wind turbine rotor carried out at the water flume at Technical University of Denmark (DTU). The rotor is three-bladed and designed using Glauert theory for the tip speed ratio of 5 with a constant design lift coefficient along the span of 0.8. The measurements include dye visualization, Particle Image Velocimetry and Laser Doppler Anemometry. The wake instability has been studied in the range of tip speed ratio of 3 - 9 at different cross sections from the very near wake up to 10 rotor diameters downstream from the rotor. The initial flume flow was subject to a very low turbulence level with a uniform velocity profile, limiting the influence of external disturbances of the inherent vortex instability. Using PIV measurements and visualization, special attention was paid to detect and categorize different types of wake instabilities and the development of the flow in the near and the far wake. In parallel to PIV, LDA measurements provided data for various rotor regimes, revealing the existence of three main regular frequencies governing the development of different processes and instabilities in the rotor wake. In the far wake a constant frequency corresponding to the Strouhal number was found for the long-scale instabilities. This Strouhal number is in good agreement with the well-known constant that usually characterizes the oscillation in wakes behind bluff bodies. From associated visualizations and reconstructions of the flow field, it was found that the dynamics of the far wake is associated with the precession (rotation) of a helical vortex core. The data indicate that Strouhal number of this precession is independent of the rotor angular speed.

Nazarinia, M., Soltani, M. R. and Ghorbanian, K.

"EXPERIMENTAL STUDY OF VORTEX SHAPES BEHIND A WING EQUIPPED WITH DIFFERENT WINGLETS"

Journal of Aerospace Science and Technology, Vol. 3, No. 1, 2006, pp. 1-15.

An extensive experimental study is conducted to examine the effects of different winglet shapes and orientations on the vortex behind a wing, static surface pressure over the wing, and wake of a swept wing at various angles of attack. Four types of winglets, spiroid (forward and aft), blended, and wing grid are used in this investigation. Wing static surface pressure measurements are obtained for both chordwise and spanwise as well as the wake profiles at various angles of attack using the winglets. The data are compared with those without winglet -- that is, bare wing. The results show that integration of winglets change the flowfield over and around the wing significantly. Further, it is found that certain winglet configurations improve both the wake and the wing pressure distribution. The total pressure in the wake of the model varies drastically when the wing is equipped with winglets.

Nedungadi, A. and Lewis, M. J.

"COMPUTATIONAL STUDY OF THREE-DIMENSIONAL OBLIQUE SHOCK WAVE/VORTEX INTERACTION"

AIAA Paper No. 1995-2770, July 1995, San Diego, CA.

A numerical study has been conducted to study the three-dimensional oblique shock wave/vortex interaction (OSVI) to investigate the effects of Mach number, vortex strength, and ratio of the vortex axial to freestream velocity. The three-dimensional, unsteady, compressible Euler equations are solved

to simulate the OSVI. An analytical vortex model is prescribed at the inflow and allowed to interact with an existing oblique shock. The axial velocity through the vortex core has a deficit which is characteristic of supersonic stream-wise vortices. Three distinct flowfield structures are obtained depending on vortex strength and ratio of the vortex axial to freestream velocity. Weak interaction was characterized by minimal change in vortex strength and shock structure while a moderate interaction results in regions of subsonic flow. The strong interaction results in vortex breakdown, dramatic change in shock structure, and region of reversed flow. Streamwise redistribution of vorticity was also calculated and was found to be largest for the strong interaction while the weak interaction resulted in very small changes of vorticity levels.

Nedungadi, A. and Lewis, M. J.

"COMPUTATIONAL STUDY OF THE FLOWFIELDS ASSOCIATED WITH OBLIQUE SHOCK/VORTEX INTERACTIONS"

AIAA Journal, Vol. 34, No. 12, December 1996, pp. 2545-2553

The interaction between a supersonic streamwise vortex and an oblique shock is solved numerically using unsteady, three-dimensional Euler equations. The parametric study ascertains the effects of vortex strength, streamwise velocity deficit, and Mach number on the oblique shock/vortex interaction. The vortex, whose tangential and streamwise velocities are analytically modeled, is introduced upstream of the shock and allowed to interact with the shock. The interaction is examined at freestream Mach numbers of 3 and 5, using vortices of varying strength and possessing various velocity deficits. Three distinct types of interactions -- weak, moderate, and strong -- are observed, depending very strongly on the streamwise velocity deficit and, to a lesser degree, on the strength of the vortex. The weak interaction is characterized by a slight distortion of the shock and vortex with the resulting flowfield being supersonic everywhere. The moderate interaction, however, results in a more pronounced distortion of the shock, creating a small pocket of subsonic flow downstream of the interaction. In addition, the incident vortex is highly distorted by the shock and eventually splits up into two counter-rotating vortices. In the strong interaction, due to the formation of a large subsonic region, a dramatic reorganization of the original shock occurs, accompanied by a region of reversed subsonic flow, a stagnation point, and a drastic expansion of the vortex core, all of which are characteristics of vortex breakdown.

Nedungadi, A. and Lewis, M. J.

"NUMERICAL SIMULATIONS OF OBLIQUE SHOCK/VORTEX INTERACTIONS RESULTING IN VORTEX BREAKDOWN"

AIAA Paper No. 1997-0068, January 1997, Reno, NV.

The interaction between a supersonic streamwise vortex and an oblique shock is solved numerically using the unsteady, three-dimensional, Euler equations. In particular, the strength of the incident vortex and oblique shock are chosen such that the oblique shock/vortex interaction results in vortex

breakdown. The flowfield associated with vortex breakdown is analyzed and the effects of Mach number on vortex breakdown are presented. Due to the deficit in Mach number through the vortex core, the incident vortex breaks down, creating a large subsonic, reversed flow region. This subsonic region acts as if it were a bluff body in a supersonic stream, and the outer flow responds by creating a three-dimensional shock around it. It is observed that the static pressure within the recirculating bubble approaches stagnation pressure and that the axial velocity approaches zero. These two observations seem to indicate the possibility of vortex breakdown. It is also observed that when the vortex and shock strength are maintained, the axial extent of the breakdown region remains the same in the Mach number range examined; though the shape is dependent on the Mach number.

Nedungadi, A. and Lewis, M. J.

"NUMERICAL STUDY OF FUEL MIXING ENHANCEMENT USING AN OBLIQUE SHOCK/VORTEX INTERACTION"

Journal of Propulsion and Power, Vol. 16, No. 6, Nov.-Dec. 2000, pp. 946-955.

The effects of swirl and jet-to-freestream pressure ratio on the mixing performance of a swirling helium jet interacting with an oblique shock are investigated. The three-dimensional parabolized Navier-Stokes equations are solved to simulate the parallel injection of a swirling helium jet at Mach 3 into a coflowing stream of air at Mach 4. The effects of swirl and jet-to-freestream pressure ratios on the mixing performance are studied by considering various strengths for the swirling jet and various jet exit pressures, respectively. The mixing performance is based on several parameters that include the maximum helium mass fraction decay, the fraction of total helium mass flux present at various concentrations, and the total entropy rise. It is shown that the fraction of total helium mass flux that is present at a helium mass fraction of less than or equal to 0.05 increases from 8 to 16 percent and that the point at which pure helium ceases to exist occurs farther upstream with the addition of swirl. Furthermore, it is shown that the jet with the lower pressure and momentum provides better mixing performance than the higher pressure jet.

Neece, R. T.

"WAKE VORTEX RADAR SYSTEM DEVELOPMENT"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 299-308

An investigation of radar sensors for aircraft wake vortices is being conducted by NASA. The stated objective is to investigate microwave and millimeter wave sensors to locate, track, and observe the wake vortex hazard. Initially all-weather capability was the objective and early studies concentrated on the clear air detection problem. These studies included scattering and reflectivity studies, radar systems investigations, and clear air field experiments at X and C band. Bragg scattering from refractive index variations over small eddies was determined to be the most reliable natural reflectivity mechanism, and Bragg scattering by acoustic waves was also investigated. Clear air field

measurements were conducted at Wallops Flight Facility, White Sands Missile Range, with Lockheed Martin, and at Baltimore Washington International Airport, with the Applied Physics Laboratory. Results in clear air were marginal, indicating that developing a clear air detection system would be problematic. The focus has now changed to developing a low-visibility radar that will compliment a lidar wake vortex sensor. A 35 GHz pulsed Doppler radar is currently being assembled for field testing in 1998.

Neece, R. T., Britt, C. L., White, J. H., Mudukutore, A., Nguyen, C. and Hooper, B.

"WAKE VORTEX TRACKING USING A 35 GHz PULSED DOPPLER RADAR"

5th NASA Integrated CNS Conference and Workshop, Fairfax, VA, May 2005

A 35 GHz, pulsed-Doppler radar system has been designed and assembled for wake vortex detection and tracking in low visibility conditions. There is a potential for significant airport efficiency improvement, if a system can be employed to aid regulators and pilots in setting safe and efficient following distances based on airport conditions. To fill the need for detection capability in low-visibility conditions, a 35 GHz, pulsed-Doppler radar system is being investigated for use as a complimentary, low-visibility sensor for wake vortices. The radar sensor provides spatial and temporal information like that provided by Lidar, but under weather conditions that a Lidar cannot penetrate. Currently, we are analyzing the radar design based upon the data and experience gained during the wake vortex Lidar deployment with AVOSS at Dallas/Fort Worth International Airport. As part of this study, two numerical models were utilized in system simulations. The results of this study improve our understanding of the method of detection, resolution requirements for range and azimuth, pulse compression, and performance prediction. Simulations, applying pulse compression techniques show that detection is good in heavy fog to greater than 2000 m. Both compressed and uncompressed short pulses show the vortex structure. To explore operational challenges, siting and scanning strategies were also analyzed. Simulation results indicate that excellent wake vortex detection, tracking and classification is possible in drizzle (+15 dBZ) and heavy fog (-13 dBZ) using short pulse techniques (<99 ns) at ranges on the order of 900 m, with a modest power of 500 W output. At 1600 m, detection can be expected at reflectivities as low as -13 dBZ (heavy fog). The radar system, as designed and built, has the potential to support field studies of a wake vortex spacing system in low-visibility conditions ranging from heavy fog to rain, when sited within 2000 m of the flight path.

Nelkin, M.

"IN WHAT SENSE IS TURBULENCE AN UNSOLVED PROBLEM?"

Science, Vol. 255, January 1992, pp. 566-570.

Turbulence can be narrowly defined as a property of incompressible fluid flow at very high Reynolds number, and thus an attempt can be made to specify what is and what is not understood about it. The applicability of the Navier-Stokes equations of hydrodynamics to real turbulent flows and the success and limitations of direct numerical simulation are considered. A discussion is presented of universality,

and mention is made of the remarkable success of Kolmogorov's 1941 scaling ideas despite uncertainties about basic underlying assumptions such as local isotropy. Extensions of this scaling to the multifractal picture of dissipation fluctuations are discussed, but this picture remains phenomenological. Turbulence as defined above remains 'unsolved' in the sense that a clear physical understanding of the observed phenomena does not exist.

Nelson, B., Williams, M. and Wood, L.

"SAFETY STUDY OF CLOSELY SPACED PARALLEL OPERATIONS UTILIZING PAIRED APPROACH"

DOT-FAA-AFS-400-2019-R-25, April 2019, FAA Flight Technologies and Procedures Division, Washington, DC.

This is an FAA report entitled 'Safety Study of Closely Spaced Parallel Operations Utilizing Paired Approach.' This study analyzed collision risk in the event of a course deviation by the lead aircraft in a Paired Approach operation. The closest in-trail distances deemed acceptable for the operation, referred to as collision safety limits, are identified. The study utilized fast-time simulations to assess collision risk for various in-trail starting distances at select locations along the approach. Major factors contributing to the collision safety limit include the difference in speed between the lead and trailing aircraft, runway centerline spacing, and the type of runway approach alignment (i.e., straight-in or offset).

Nelson, C. C., Cain, A. B. and Morris, P. J.

"SIMULATIONS OF HIGH SPEED IMPINGING JETS"

AIAA Paper No. 2012-0831, January 2012, Nashville, TN.

Time accurate simulation of a high-speed impinging jet configuration was performed using both the RANS-based Wind-US production flow solver and the CHOPA computational aeroacoustics solver. Qualitatively, the Wind-US solution predicted many of the major features observed experimentally for this flow. Though direct comparison with experiment was not possible, the predicted peak sound pressure level and frequency appears reasonable considering the published observations. The observed helical character of the jet plume was also predicted, at least in part. Our initial efforts to model this flow with the CHOPA solver, while not complete, are beginning to produce reasonable-looking results, though a full assessment is not possible until the simulation is complete.

Nelson, R. C.

"THE TRAILING VORTEX WAKE HAZARD: BEYOND THE TAKEOFF AND LANDING CORRIDORS"

AIAA Paper No. 2004-5171, Providence, RI, August 2004

This paper focuses on issues related to the trailing vortex wake hazard beyond the takeoff and landing corridors. The operational procedures adopted by the FAA in the 1970s for avoiding wake turbulence encounters in the take-off and landing corridors have been very successful in providing commercial

aviation with a high degree of safety. However, there is a growing body of evidence that encounters well beyond the immediate airport area could also prove to be hazardous. A review of commercial airline accidents for which a wake vortex encounter was a contributing factor in the accident are reviewed. Another problem that is addressed is wake encounters at cruise altitude. In the current study the vortex induced loads created by wake vortices at cruise altitude are examined.

Nelson, R. C.

"TRAILING VORTEX WAKE ENCOUNTERS AT ALTITUDE - A POTENTIAL FLIGHT SAFETY ISSUE?"

AIAA Paper No. 2006-6268, Keystone, CO, August 200.

The potential hazard of one aircraft encountering the trailing vortex wake of another aircraft during either take-off or landing is well known. The wake vortex hazard in the terminal area has been virtually eliminated using the operational procedures and aircraft separation criteria mandated by the air traffic authorities. This paper presents arguments that wake encounters at cruise altitude are a potential safety issue that needs to be examined. Wake vortex encounters at cruise altitudes are likely to increase due to three factors. These factors include; the reduction of the minimum vertical separation distances between aircraft, the increased air traffic allowed by the reduced vertical separations, and the large difference in the size of aircraft operating at the cruise altitudes. The arguments are supported by simple analysis and a review of simulation and flight test results obtained from earlier studies of wake encounters at low altitudes. Simple analysis techniques show that the rolling moment induced on a following aircraft is comparable in magnitude to that which could occur during take-off or landing. In addition, reported wake encounters at cruise altitude are discussed.

Nelson, R. C.

"TRAILING VORTEX WAKE DISTORTION AND ITS INFLUENCE ON AIRCRAFT SAFETY"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

This presentation examines the response of an airplane to an encounter with the trailing vortex wake generated by another airplane. Using simplified analysis techniques, key factors that affect the vortex-induced rolling moment on a penetrating airplane wing are presented. Simple strip theory and lifting line theory were used to estimate the rolling moment induced on the wing penetrating a trailing vortex wake. To test the validity of using simple strip theory or lifting theory to predict the vortex induced rolling moments, the methods were evaluated by comparing the predictions with experimental measurements. Experimental data obtained by NASA was used to evaluate the prediction methods. The data included measurements of the vortex velocity field and the roll moment induced on a wing located in the trailing vortex wake. The predictions were found to give good estimates of the vortex induced loads.

Nelson, R. C.

"THE DYNAMIC RESPONSE OF AIRCRAFT ENCOUNTERING AIRCRAFT WAKE TURBULENCE"

Ph.D. Thesis, June 1974, Penn. State Univ., University Park, PA

This investigation deals with the dynamic behavior of an airplane encountering aircraft wake turbulence. A digital computer simulation was developed to study the response of an aircraft flying into a trailing vortex wake. The simulation includes the complete six degree of freedom equations of motion, a description of the vortex velocity field, unsteady aerodynamics, and pilot control input. The parameters, varied in this simulation, include the penetration angle, separation distance, aircraft size (for both the penetrating and generating aircraft), and pilot control input (single- or multi-axes). Predicted vortex induced motions are presented for a variety of probe aircraft. The probe aircraft selected are representative of general aviation, business, and light jet transport type aircraft. The aircraft used to generate the vortex wakes are representative of the commercial transport fleet. The computer predictions indicate that relatively large aircraft (light jet transport) can experience unacceptable vortex-induced roll excursions.

Nelson, R. C.

"THE RESPONSE OF AIRCRAFT ENCOUNTERING AIRCRAFT WAKE TURBULENCE"

AFFDL-TR-74-29, June 1974, Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH

The investigation deals with the dynamic behavior of an airplane encountering aircraft wake turbulence. A digital computer simulation was developed to study the response of an aircraft flying into a trailing vortex wake. The simulation includes the complete six degrees of freedom equations of motion, a description of the vortex velocity field, unsteady aerodynamics, and pilot control input. The parameters varied in this simulation include the penetration angle, separation distance, aircraft size, and pilot control input.

Nelson, R. C.

"DYNAMIC BEHAVIOR OF AN AIRCRAFT ENCOUNTERING AIRCRAFT WAKE TURBULENCE"

J. Aircraft, Vol. 13, No. 9, September 1976, pp. 704-708

This paper deals with the dynamic behavior of an airplane encountering aircraft wake turbulence. A digital computer simulation was developed to study the response of an aircraft flying into a trailing vortex wake. The simulation includes the complete six degree-of-freedom equations of motion, a description of the vortex velocity field, unsteady aerodynamics, and pilot control input. The parameters, varied in this simulation, include the penetration angle, separation distance, aircraft size (for both the penetrating and generating aircraft), and pilot control input (single or multi-axes). It was found that pilot control input could be momentarily out of phase with the vortex induced disturbance. Thus, in certain cases, the pilot's control input would tend to aggravate the vortex-induced upset.

Nelson, R. C. and Babie, B. M.

"AN EXPERIMENTAL STUDY OF THE STABILITY OF A FOUR-VORTEX SYTEM"

AIAA Paper No. 2005-4852, Toronto, Canada, June 2005

An experiment is currently being conducted at the University of Notre Dame to investigate the interactions, and ultimately the instabilities, that persist in a four-vortex wake. A wake consisting of four trailing vortices was created in Notre Dame's atmospheric boundary layer wind tunnel. The advantage of this tunnel is the long test section, which permits the observation of wake interactions at distances up to thirty wake-spans downstream of the point of generation. The wake was created by four high aspect ratio wing models such that the circulation strength and the spacing between each vortex in the wake may be controlled. The principal aim of this study is to experimentally determine the optimal configurations, based on circulation strength and spacing, that are consistent with the rapid amplification of certain wake vortex instability modes. The primary method for evaluating the experimental facility has been flow visualization. Helium bubbles were introduced into the core region of individual vortices to visualize these wake structures. This paper presents some early results from the visualization of the four-vortex wake. These results suggest that the use of helium bubbles is a suitable method for visualizing wake vortices for the full length of the test section.

Nelson, R. C. and Jumper, E. J.

"AIRCRAFT WAKE VORTICES AND THEIR EFFECT ON FOLLOWING AIRCRAFT"

AIAA Paper No. 2001-4073, Montreal, Canada, August 2001

This paper discusses the response of an airplane to an encounter with the trailing vortex wake generated by another airplane. A simplified analysis is used to identify key factors that affect the vortex-induced rolling moment. This is followed by selected simulation results that show how sensitive the upset response is to how the aircraft enters the vortex wake. Entry angle and pilot input were important factors in determining the maximum upset angle. Finally, the idea of wing design features to reduce the vortex hazard is reviewed.

Nelson, R. C. and McCormick, B. W.

"THE DYNAMIC BEHAVIOR OF AN AIRCRAFT ENCOUNTERING AIRCRAFT WAKE TURBULENCE"

AIAA Paper No. 1974-0774, Anaheim, CA, 1974

This paper deals with the dynamic behavior of an airplane encountering aircraft wake turbulence. A simplified analysis is presented in which the various factors influencing the vortex-induced rolling moment are examined. Based upon this simplified analysis, a method is developed which allows a rapid estimate of the vortex induced rolling moment to be made. Also, results from a digital computer simulation of the aircraft vortex penetration are presented. The computer predictions indicate that relatively large aircraft (80,000 lb. jet transport) can experience unacceptable vortex-induced roll excursions. Also, the results from the simulation were found to compare favorably with flight test

results. In addition to evaluating the vortex-induced responses, the effect of pilot control input was assessed. It was found that pilot control inputs were momentarily out of phase with the vortex-induced disturbance. Thus, the pilot's control inputs tended to aggravate the vortex-induced upsets.

Nelson, R. C. and McCormick, B. W.

"AIRCRAFT-VORTEX PENETRATION"

SAE Paper No. 730296, Wichita, KS, 1973

As a result of research programs, the hazard of wake turbulence to light aircraft has been well documented. In this paper it is emphasized that relatively large aircraft can also be susceptible to vortices generated by large jet transports. This conclusion is based upon a review of accident records and the results from a computer simulation of the aircraft-vortex interaction. The computer simulation consists of the equations of motion with six degrees of freedom as well as control input by the pilot.

Nelson, R. C. and Tartaglione, J. J.

"CORRELATION OF TRAILING VORTEX DATA OBTAINED FROM FLIGHT TEST MEASUREMENTS"

AIAA General Aviation Technologyfest, November 1977, Wichita, KS.

There are several theories which can be used to predict the rate of decay of the velocities within a trailing vortex wake. Iversen proposed a method of correlating trailing vortex data based upon a variable eddy viscosity vortex decay model. Flight test data collected using the tower fly-by technique is used to show that Iversen's technique can be used to successfully collapse the data to a single curve, despite the differences in aircraft size and operating conditions.

Nelson, W. C.

"AIRFOIL TIP VORTEX CONTROL"

US Patent 4,017,041, April 1977

Device for diminishing tip vortices in an aircraft. For the purpose of diminishing the tip vortices generated by aircraft there are provided retractable foils at or near the airfoil, as wing, tips in question and projecting upwardly and/or downwardly therefrom. The operation of the retractable foils is satisfactory if such foils are parallel to the centerline of the aircraft but it is preferable if such foils are angled slightly with respect thereto, such as if the leading edge of the upper foil is angled approximately 10 degrees inwardly toward the fuselage of the aircraft and the bottom foil is oppositely angled also approximately 10 degrees. The retractable foils, in addition to diminishing wing tip vortices, also when used on wing tips improve the rate of climb of an aircraft at a given engine setting and appear to diminish the area over which the major amounts of noise generated by the aircraft will be dispersed. The foils may be fully retractable into the aircraft wing, but if not fully retracted, they will each provide a small streamlined ridge projecting upwardly and/or downwardly adjacent the tip of the

aircraft wings which will improve the lift characteristics of the wings by diminishing air flow around the end of the wings sufficiently to move than compensate for the drag otherwise created. The foils are also advantageously applicable to other aircraft components, such as flaps, stabilizers or elevators.

Nemes, A., Sherry, M., Lo Jacono, D., Blackburn, H. M. and Sheridan, J.

"EVOLUTION AND BREAKDOWN OF HELICAL VORTEX WAKES BEHIND A WIND TURBINE"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012077-1 - 012077-11.

The wake behind a three-bladed Glauert model rotor in a water channel was investigated. Planar particle image velocimetry was used to measure the velocity fields on the wake center-line, with snapshots phase-locked to blade position of the rotor. Phase-locked averages of the velocity and vorticity fields are shown, with tip vortex interaction and entanglement of the helical filaments elucidated. Proper orthogonal decomposition and topology-based vortex identification are used to filter the PIV images for coherent structures and locate vortex cores. Application of these methods to the instantaneous data reveals unsteady behavior of the helical filaments that is statistically quantifiable.

Nespor, J. D., Hudson, B., Stegall, R. L. and Freedman, J. E.

"DOPPLER RADAR DETECTION OF VORTEX HAZARD INDICATORS"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 37-1 - 37-43

Wake vortex experiments were conducted at White Sands Missile Range, NM using the AN/MPS-39 Multiple Object Tracking Radar (MOTR). The purpose of these experiments was twofold. The first objective was to verify that radar returns from wake vortex are observed for some time after the passage of an aircraft. The second objective was to verify that other vortex hazard indicators such as ambient wind speed and direction could also be detected. The present study addresses the Doppler characteristics of wake vortex and clear air returns based upon measurements employing MOTR, a very sensitive C-Band phased array radar. In this regard, the experiment was conducted so that the spectral characteristics could be determined on a dwell-to-dwell basis. Results are presented from measurements of the backscattered power, velocity, and spectral width when the aircraft flies transverse and axial to the radar beam. The statistics of the backscattered power and spectral width for each case are given. In addition, the scan strategy, experimental test procedure and radar parameters are presented.

Neubert Jr., D. E.

"TRAILING VORTEX / FREE-SURFACE INTERACTION"

MS Thesis, December 1992, Naval Postgraduate School, Monterey, CA.

An investigation of the interaction of a trailing vortex with a free surface has been undertaken for the purpose of understanding the origin of scars and striations. Velocity and turbulence measurements have been carried out using a Laser-Doppler Velocimeter (LDV) for various positions of the vortex relative to the free surface. The results have shown that the vortex motion affects the free surface and is affected by it. This mutual interaction leads to the development of surface scars comprised primarily of heterotrophic vortices normal to the free surface. Furthermore, the velocity and turbulence characteristics are affected such that the vertical components of turbulence decay rapidly and the horizontal components stretch in the horizontal plane. The experiments have provided sufficient understanding of the physics of the phenomenon for the subsequent undertaking of the development of a predictive numerical model.

Neuhart, D. H., Greene, G. C., Satran, D. R. and Holbrook, G. T.

"DENSITY STRATIFICATION EFFECTS ON WAKE VORTEX DECAY"

J. Aircraft, Vol. 23, No. 11, November 1986, pp. 820-824

Results of an experimental study to determine the effects of density stratification on wake vortex decay are presented. The range of stratification commonly encountered in the atmosphere was simulated in the Vortex Research Facility at NASA Langley Research Center by variations in the vertical temperature gradient. Wake measurements were made for low and high aspect ratio, swept and unswept wings at chord Reynolds numbers of about 2×10^5 to 6×10^5 . The results indicate that, in the absence of turbulence, density stratification can determine wake descent distance and lifetime. A comparison of laboratory and flight-test measurements with a vortex decay model suggests a significant Reynolds number effect on wake vortex decay.

Nevill, R. G.

"DOPPLER SONAR IN DETECTION OF AIRCRAFT WAKES"

AT-2027-098-ASA, November 1974, Univ. of Birmingham, Birmingham, England

Doppler sonar remote velocity probes have been proposed as means of detecting and locating the hazardous wingtip vortices shed by heavy aircraft. A theoretical model is discussed in which the target strength is related to the energy dissipation in the vortex core and to the angle of scatter. This model includes a modification of existing scattering theory to account for the refraction expected in a real aircraft wake. An experiment designed to evaluate the acoustic target strength in a vortex core and assess the range of frequencies suitable for acoustic probing, is described. A brief trial of a doppler sonar equipment in conjunction with independent wake monitors at an airport is also reported.

New, T. H., Shi, S. and Zang, B.

"SOME OBSERVATIONS ON VORTEX-RING COLLISIONS UPON INCLINED SURFACES"

Experiments in Fluids, Vol. 57, 2016, pp. 109-1 to 109-18.

This paper reports upon a laser-induced fluorescence visualization and time-resolved particle image velocimetry study to resolve the detailed dynamics associated with $Re = 2000$ and 4000 circular vortex rings colliding with 30 – 77 -degree inclined surfaces. Two-dimensional visualization results show that larger inclination angles lead to increasingly rapid size reduction in the primary vortex-ring core closer to the surface, faster formation of the secondary vortex-ring core, and subsequent ingestion by the former. In contrast, primary vortex-ring core further away from the surface becomes physically larger and incoherent more rapidly, with slower formation and entrainment of the secondary vortex-ring core. Interestingly, a vortex dipole and small vortex-ring-like structure are produced for the largest inclination angle of 75 degrees, possibly due to vortex disconnection and reconnection processes. Results taken along the non-inclined plane show significant bulging of the primary vortex-ring cores when the inclination angle increases from 30 degrees onwards. More importantly, additional vortex cores are observed to entwine with the primary vortex-ring core and provide strong direct evidence for the bi-helical vortex line flow mechanism put forward by Lim Exp Fluids 7:453-463, 1989). Lastly, the behavior of the primary and secondary vortex-ring cores further away from the surface is highly sensitive towards the state of the bi-helical lines compressed at that region. Strong compression driven by circumferential flows due to large inclination angles may explain the unique flow structures and behavior observed for 75 degree inclination angle here.

Newman, B. G.

"FLOW IN A VISCOUS TRAILING VORTEX"

Aero. Quarterly, Vol. 10, May 1959, pp. 149-162

The equations of motion for an isolated laminar viscous vortex at moderate to large Reynolds numbers are linearized, by assuming that both the rotational velocity and the deficit of longitudinal velocity are small compared with that in the free stream. The rotational motion and the longitudinal motion may then be superimposed and solutions are readily obtained for each. If the vortex is generated by a body with profile drag it is predicted that the deficit of longitudinal velocity will be positive, which is in agreement with experimental observation. Further details of the solution and its relation to the flow in real vortices are discussed; and the theory is compared with some measurements in a turbulent vortex.

Newman, S., Brown, R., Perry, J., Lewis, S., Orchard, M. and Modha, A.

"COMPARATIVE NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF THE VORTEX RING PHENOMENON IN ROTORCRAFT"

57th Annual Forum of the American Helicopter Society, Washington, DC, May 2001

The boundary for the onset of vortex ring flow breakdown in low-speed flight is derived from a physical hypothesis expressed as an extension of simple momentum theory. Predictions are adjusted to accord with measurements found in the literature and with some further deductions made regarding the nature of the flow in the vortex ring state. The opportunity is taken to investigate the details of the flow using a new numerical analysis of the unsteady rotor wake. By maintaining diffusion of vorticity at very low levels, the numerical approach fulfils an essential requirement for modelling the vortex ring condition, since vortices can persist for a long time in the vicinity of the rotor disk. The numerical analysis is compared with test data in the literature as well as with recently generated model rotor data. The numerical analysis supports the assumptions made in deducing the boundary for the onset of vortex ring. The complexity of the flow within the vortex ring/turbulent wake flow states is also revealed. The work has shown that it is possible to calculate and understand the details of the flow in the vortex ring and turbulent wake regimes. The numerical analysis suggests that apparently minor variables can affect the flow, and that variations in these variables may account for some of the contradictions in past results that have made these regimes somewhat mysterious.

Ng, T. T. and Oliver, D. R.

"LEADING EDGE VORTEX AND SHEAR LAYER INSTABILITIES"

AIAA Paper No. 98-0313, Reno, NV, January 1998

The stability of a leading-edge vortex was studied using available flow visualization and velocity data. The development of a vortex can be envisioned to compose of three possible stages. During the initial stage, the shear layer and its associated vorticity immediately downstream from the apex coalesce to form a primary vortex core. During this stage the vortex flow resembles a forced vortex. When the primary core is sufficiently developed, the secondary vortex becomes a prominent perturbation along the leading edge. The induced cross flow instability leads to the formation of stable, co-rotating, streamwise vortex filaments in the separated shear layer. A second stage of development occurs where the straining field of the main vortex amplifies the secondary instability near the saddle point in-between a co-rotating shear layer vortex pair. This leads eventually to the formation of a secondary vortex core consisting of a series of vortices with an opposite sense of rotation to the primary core. A vortex system as such violates the circulation distribution criterion for helical flow stability, and the vortex becomes centrifugally unstable. If the growth rate of the instability is sufficiently fast compared with the convection rate, a third stage of development occurs over the wing. The expected result is an expansion of the vortex cross-section or vortex breakdown, with the circulation eventually re-establishing a stable distribution.

Nguyen, D. P. C.

"MAY 26 - JUNE 6, 1997 JFK2 DEPLOYMENT: WAKE VORTEX MEASUREMENTS AT JOHN F. KENNEDY INTERNATIONAL AIRPORT FOR A 2.02 MICRON PULSED COHERENT LIDAR, A 10.6 MICRON CW LIDAR, AND A GROUND WIND VORTEX SENSING SYSTEM"

RTI/4903-032-03S, August 1998, Center for Aerospace Technology, Research Triangle Institute, Hampton, V.

From May 26 through June 6, 1997, the Wake Vortex Lidar Project from NASA Langley Research Center deployed a 2.02-micron pulsed lidar to John F. Kennedy (JFK) International Airport to assess its performance capabilities with other previously field-tested wake measurement sensors. In November 1996, tests were simultaneously conducted with several other wake vortex and meteorological sensors in the middle marker region of Runway 31R. The latest deployment to JFK included the same 10-micron continuous wave (CW) lidar from MIT/LL and the ground-based anemometer array from the Volpe Center. Correlating wake vortex data was gathered and compared for all three participating wake vortex measurement sensors.

Ni, B., Zhang, A., Yao, X. and Wang, B.

"NUMERICAL SIMULATION OF TRAJECTORY AND DEFORMATION OF BUBBLE IN TIP VORTEX"

Applied Mathematics and Mechanics, Vol. 33, No. 6, 2012, pp. 701-716.

According to the behaviors of a bubble in the ship wake flow, the numerical simulation is divided into two stages, quasi-spherical motion and non-spherical motion, based on whether the bubble is captured by the vortex or not. The one-way coupled particle tracking method and the boundary element method are adopted to simulate these two stages, respectively. Meanwhile, the initial condition of the second stage is taken as the output of the first one, and the entire simulation is connected and completed. Based on the numerical results and the published experimental data, the cavitation inception is studied, and the bubble is tracked. Besides, the split of the bubble captured by the vortex and the following sub-bubbles are simulated, including motion, deformation, and collapse. The results provide some insight into the control on wake bubbles and optimization of the wake flow.

Nichols, R. H.

"ALGORITHM AND TURBULENCE MODEL REQUIREMENTS FOR SIMULATING VORTICAL FLOWS"

AIAA Paper No. 2008-337, Reno, NV, January 2008

Navier-Stokes computational results using a 3rd order spatial upwind flux algorithm and two 5th order spatial WENO algorithms are compared for a wing tip vortex configuration and for a forebody at angle-of-attack. Rotational and curvature corrections and Detached Eddy Simulation (DES) variations of the Spalart-Allmaras (SA) and Shear Stress Transport (SST) turbulence models are also investigated. The results for these two test cases demonstrate that higher order fluxes improve the prediction of the vortex significantly as it is convected downstream from the body. The rotationally corrected SA model reduced the eddy viscosity in the vortex core region and provided a much-improved solution of the vortex over the baseline SA model. The SST DES model solution was also more accurate in the vortex core region than the baseline SST model.

Nichols, T., Argrow, B. and Kingston, D.

"ERROR SENSITIVITY ANALYSIS OF SMALL UAS WIND-SENSING SYSTEMS"

AIAA Paper 2017-0647, January 2017, Grapevine, TX.

A mathematical investigation is made into sources of error in inertial wind measurements made from small unmanned aircraft systems with the objective of broadly determining the nature and significance of errors in the relative wind; state estimation; and pressure, temperature and humidity subsystems as well as errors that result from physical and temporal alignment errors between these systems. Errors in inertial vehicle velocity, relative wind measurement and angular alignment of state estimation and relative wind sensing systems are shown to have the greatest impact. A new approach to identifying possible error sources based on periodicity of errors in the aircraft yaw angle, that flows from the error mathematics, is also presented and demonstrated in a simple flight test case.

Nicks, O. W.

"EXPERIMENTAL COMPARISON OF TWO WING TIPS"

Technical Soaring, Vol. XIV, No. 3, 1990, pp. 81-88.

Systematic tests of six wing tip configurations chosen for a general aviation application had shown a sharp-edged tip to be best for a range of conditions. A full-sized model was made from the outer five feet of a 15-meter glider wing having a drooped tip. The model was made to allow tips to be interchanged, and a sharp-edged tip like that developed for the general aviation application was tested on a direct comparison basis with the original glider tip. At full scale Reynolds numbers, the model tests showed the new sharp-edged tip to be superior for all values of lift coefficient above 0.4. In addition to gains in L/D of up to 6%, the climb parameter was significantly improved by as much as 6%, and the increase in maximum lift coefficient of 4% could offer a reduced stall speed. From earlier tests of a general aviation application, an increase in effective dihedral at high angles of attack can also be expected. Flow field surveys were made of the wake downstream of the tip, to determine the nature and location of the vortices. These showed a distinct effect on the location and strength of the vortices and appear to corroborate the higher lift of the new tip.

Nicolaon, J. P.

"OPTIMISED WAKE VORTEX SEPARATION STANDARDS IN THE NEAR- AND FAR-TERM"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

Eurocontrol has launched a high-level project, WakeSep, which attempts to federate research currently ongoing in Europe, as well as identifying gaps where new projects are needed, to support the operational implementation of Wake Vortex-based separations. WakeSep takes as far-term objective the concept described by ATC_Wake in Europe and like that of WakeVAS in the USA. It also identifies the set of enablers that need to be in place for such a concept to be implemented. In this presentation

we describe for certain of these enablers the issues that must be addressed to reach the far term solution. In particular, the impact on detection and prediction of wake-vortices of uncertainty in the forecasting of weather is considered. Meteorological conditions will have a major impact on the possibility of capacity gains in two areas. Firstly, current WV detection equipment will not support operational usage in heavy rain or under low visibility conditions. Secondly, the difficulty to accurately accommodate real weather conditions in WV prediction models will influence the confidence that can be placed in the predictions and thus in the separations that can be applied. This problem is exacerbated by variations due to the local topology which would require a detailed validation of the model at each airport. It seems likely that deterministic predictive models will not be able to produce sufficiently reliable results so that there is a need to adopt a more probabilistic approach. Eurocontrol will launch an action next year to identify the main European airports which are capacity-constrained by WV. For the high potential airports, it is intended to undertake a meteorological and WV data collection over a full year. The notion of weather classes introduced in SWake will be used to create a statistical model of WV behavior specific to that airport.

Nicolosi, F., De Marco, A., Sabetta, V. and Vecchia, P. D.

"ROLL PERFORMANCE ASSESSMENT OF A LIGHT AIRCRAFT: FLIGHT TESTS AND FLIGHT SIMULATION"

AIAA Paper 2015-2238, June 2015, Dallas, TX.

This paper deals with the assessment of roll performance of a light aircraft through several flight tests and flight simulations. The general problem of a reliable evaluation of aircraft roll performance is first discussed, including the estimation of the aerodynamic derivatives that mainly influence the airplane rolling characteristics. Next, the results of extensive flight test activities on a two-seat Tecnam P92 light aircraft are presented. The attentive analysis of many roll maneuvers performed at different flight speeds and with various aileron maximum deflections has shown unexpected good roll performance for this non-aerobatic aircraft and has been extremely useful to derive the aileron efficiency factor in non-linear conditions (high aileron deflections). Flight data have been used to extract the main aerodynamic derivatives involved and to implement an accurate flight simulation model of the aircraft. Both 1-DoF and 6-DoF Flight simulations have been used in the first part of this research to select an appropriate matrix of test conditions. Finally, when the key lateral aerodynamic derivatives were estimated from flight experiments, the resulting flight simulations have shown a very good agreement with measured time histories.

Nicolosi, F., De Marco, A., Sabetta, V. and Vecchia, P. D.

"ROLL PERFORMANCE ASSESSMENT OF A LIGHT AIRCRAFT: FLIGHT SIMULATIONS AND FLIGHT TESTS"

Aerospace Science and Technology, Vol. 76, 2018, pp. 471-483.

A methodology is presented for the roll performance assessment of a light aircraft. The study is based both on flight simulations and flight tests, focusing on the accurate determination of the lateral control power. The chosen test airplane was a Tecnam P92, a two-seat ultralight aircraft which was

specifically equipped with a lightweight and accurate instrumentation for the planned set of flight data measurements. A matrix of flight experiments for the test campaign was established with the support of 6-degree-of-freedom simulations, implementing a carefully constructed baseline dynamic model of the aircraft. The article discusses first the general problem of a reliable evaluation of aircraft roll performance indicators, i.e. the estimation of the aerodynamic derivatives that mainly influence the airplane ability to roll. Next, the results of extensive flight test activities are presented. The analysis of several roll maneuvers performed at different flight speeds and with different aileron maximum deflections showed interesting rolling characteristics for this non-aerobatic aircraft. One notable finding was a clear nonlinear dependency of the aileron efficiency index on aileron deflection amplitude. A control power derivative extracted from flight data in the form of lookup table was used to correct the baseline flight dynamics model. Flight simulations outputs based on the updated model showed a satisfactory agreement with experimental time histories. According to this, the present effort proposes a new method to estimate the aileron control derivative in whole the flight envelope for light aircraft.

Nielsen, J. N. and Schwind, R. G.

"DECAY OF A VORTEX PAIR BEHIND AN AIRCRAFT"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 413-454

A model of a trailing vortex pair behind an aircraft is presented which is thought to represent a case of extreme vortex persistency. Three stages are considered in the analysis: a rolling-up stage directly behind the aircraft, a second stage in which the vortices act independently as constant strength equilibrium turbulent vortices, and a third stage where the vortices physically interact and decay in strength. An overall theory is presented encompassing all three stages and aimed at obtaining equilibrium solutions. Calculative examples are presented for all stages.

Nielsen, J. N. and Sweberg, H. H.

"NOTE OF COMPRESSIBILITY EFFECTS ON DOWNWASH AT THE TAIL AT SUBCRITICAL SPEEDS"

NACA L-19 (originally issued as Confidential Bulletin L5009), March 1945, Langley Memorial Aeronautical Laboratory, Langley Field, VA.

Calculations have been made to show the magnitude of compressibility effects on the downwash at the tail at subcritical speeds. Experimental results of tests of two airplane models are included to give some verification of the theory. The calculations showed that the effects of compressibility on the span load distribution along the wing and on the downwash angle at the tail are small for constant values of the lift coefficient. The experimental results confirmed these calculations.

Nielsen, J. N., Stahara, S. C. and Woolley, J. P.

"INGESTION AND DISPERSION OF ENGINE EXHAUST PRODUCTS BY TRAILING VORTICES FOR SUPERSONIC FLIGHT IN THE STRATOSPHERE"

AIAA Paper No. 1974-0042, Washington, DC, 1974

Detailed analysis has been made of the ingestion and dispersion of engine exhaust products into the trailing-vortex system of a supersonic aircraft flying in the stratosphere. The rate of mixing between the supersonic jet and the co-flowing supersonic stream was found to be an order of magnitude less than would be expected on the basis of subsonic eddy-viscosity results. Ingestion started at the end of the potential core and all hot gas from the engine was ingested into the trailing vortex within two core lengths. The temperature rise in the wake of the supersonic aircraft was found to be much greater than that for a subsonic transport since temperature rise varies directly as speed squared and inversely as aspect ratio.

Nielsen, J. N., Stahara, S. S. and Woolley, J. P.

"A STUDY OF INGESTION AND DISPERSION OF ENGINE EXHAUST PRODUCTS IN TRAILING VORTEX SYSTEMS"

NASA-CR-114721, Nov, 1973, Nielsen Engineering and Research Inc., Mountain View, CA

Detailed analysis has been made of the ingestion and dispersion of engine exhaust products into the trailing vortex system of supersonic aircraft flying in the stratosphere. The rate of mixing between the supersonic jet and the co-flowing supersonic stream was found to be an order of magnitude less than would be expected based on subsonic eddy-viscosity results. The length of the potential core was 66 nozzle exit radii so that the exhaust gases remain at elevated temperatures and concentrations over much longer distances than previously estimated. Ingestion started at the end of the potential core and all hot gas from the engine was ingested into the trailing vortex within two core lengths. The vortex inhibits entrainment and thermally insulates the hot gases in the core from the stratosphere. The final buoyancy phase started only ten seconds after leaving the trailing edge. The temperature rise in the wake of the supersonic aircraft is much greater than that for a subsonic transport since temperature rise was found to vary directly as speed squared and inversely as aspect ratio. The buoyancy theory incorporates an entrainment coefficient which is a function of local turbulence conditions. Comparison between the buoyancy calculations for the supersonic case with nondimensionalized subsonic aircraft contrail data on wake spreading showed good agreement. Velocity and temperature profiles have been specified at various stages of the wake, and the analysis in this report can be used to predict variations of concentrations of species such as NO under conditions of chemical reaction.

Nightingale, A. M., Rennie, R. M., Gordeyev, S., Kelly, R., Cavalieri, D. and Jumper, E. J.

"FLIGHT-TEST MEASUREMENT OF THE AERO-OPTICAL ENVIRONMENT OF A HELICOPTER IN HOVER"

AIAA Journal, Vol. 54, No. 9, September 2016, pp. 2782-2790.

Methods and results are described for flight-test measurements of the aero-optical effect of the near-field flow surrounding a medium-sized helicopter in hover. The data were acquired using a novel, passive measurement approach in which optical wave-front aberrations were computed from the displacements of light-emitting diodes attached to a target array mounted under the helicopter fuselage. The resulting aero-optical data are shown through the rotor downwash and through the engine exhaust of the helicopter, and they are compared to estimates computed using parametric models for the helicopter wake structure and rotor-vortex diffusion. The experimental data provide additional information on the magnitude and frequency content of the aero-optical aberrations, as well as vibration data, that will be valuable for future beam-control and modeling studies.

Nikolic, V.

"A STUDY OF THE DEVELOPMENT AND ATTENUATION OF WING GENERATED, VORTICAL WAKES"

Ph.D. Thesis, June 1997, University of Notre Dame, South Bend, I.

An inviscid three-dimensional model for calculation of the roll up of wing vortex wakes was developed to address the problem of wake-vortex alleviation in a systematic way. The code was extensively tested and validated using a large body of theoretical, computational, and experimental results. During the validation, it was shown that the second moment of vorticity, heretofore assumed to be constant, not only changes as the wake evolves, but must do so to conserve energy. Further, the second moment of vorticity has been shown to be a reliable measure of the completeness of the wake roll-up process. It was demonstrated that tailoring the wing spanwise load distribution by use of flaps modifies the resulting wake in terms of making it both more diffuse and, by moving the primary vortices closer together, renders it more susceptible to the Crow far-field instability. Injection of co-rotating discrete mid-span vortices both changes the roll-up pattern and hastens the far-field instability, but causes induced drag penalties. Excitation of the far-field instability of the main wing-vortex pair by injecting relatively-weak intermediate-span discrete vortices was investigated. A new method of determining the character of vortex entrainment was developed and shown to be viable. Additionally, in an unrelated investigation performed as part of this dissertation research, it was confirmed that the wake roll up can be disorganized by implementation positive bound-circulating gradients near wing tips; however, this benefit was offset by high drag and weight penalties. Finally, some new avenues for research are suggested.

Nikolic, V. R.

"INVESTIGATION OF POSSIBLE MERIT OF GURNEY FLAP AS WAKE VORTEX-ATTENUATION DEVICE"

AIAA Paper No. 2005-4979, Toronto, Canada, June 2005

An exploratory wind tunnel investigation into the effects of two Gurney flap configurations on the formation of wake vortices, as well as on the lift and drag characteristics of a rectangular wing model, has been conducted. As expected, the Gurney flaps significantly changed the wing lift and drag, with the effects increasing with the flap size. As a new observation, the flaps brought about noticeable

changes into the near-field trailing vortex wake pattern. The differences in the rollup patterns between the baseline wing and the flapped configurations have been observed using flow visualization tufts. This simple yet effective technique has been used to gain valuable insight into the flowfield characteristics. Based on the disposition of the tufts, a new measure of the strength of the wake vortex, the rollup tightness factor has been defined and used to effectively quantitatively characterize the vortices.

Nikolic, V. R.

"PRELIMINARY STUDY OF EFFECTS OF MOVABLE TIP STRAKES ON PERFORMANCE OF RECTANGULAR WING"

AIAA Paper No. 2004-4840, Providence, RI, August 2004

A preliminary study of the effects of movable tip strakes on the aerodynamic characteristics of a rectangular wing model has been conducted in a wind tunnel. This is a new concept for controlling the flow field around wings. The addition of sharp-edged slender-delta-shaped strakes significantly modified the wing's lift and drag. When deflected symmetrically, the strakes improved the lift-to-drag ratio of the baseline wing to a large extent. The concept also seems to have potential for lateral control. There are some indications that the strakes might favorably influence the near-field rollup of the trailing vortices. This concept warrants additional more detailed investigations using various flow visualization and measurement techniques.

Nikolic, V. R.

"EFFECT OF FULL-SPAN GURNEY FLAP HEIGHT ON WING WAKE VORTEX ALLEVIATION"

Journal of Aircraft, Vol. 43, No. 5, September-October 2006, pp. 1555-1558

A series of three Gurney flaps of varying height have been studied experimentally, in combination with a baseline rectangular wing model, to examine the effects of the flap height on the wing wake vortex strength and aerodynamic efficiency. Flow visualization tufts have been used to study the vortex patterns, both qualitatively and quantitatively. It has been found that the addition of the Gurney flaps markedly altered the vortex roll-up pattern, producing weaker vortices in the near-field studied, as measured by the roll-up tightness factor. This desirable effect increased with the flap height. At the same time, the addition of the flaps caused the wing's lift-to-drag ratio to decrease, although to a degree which has been much lower than the advantageous effect on vortex strength; for example, a 10% decrease in lift-to-drag vs a 28% decrease in vortex strength for a 1.5%-chord Gurney flap at a high angle of attack. It appears noticeable vortex alleviation can be attained even with relatively low height Gurney flaps. Therefore it seems justified to investigate Gurney flaps having heights in the range 0.5-1% of the wing chord in the future. The present study clearly confirmed the usefulness of the roll-up tightness factor for quantifying vortex strengths.

Nikolic, V. R.

"ADDITIONAL AERODYNAMIC FEATURES OF WING-GURNEY FLAP FLOWS"

Journal of Aircraft, Vol. 43, No. 5, September-October 2006, pp. 1325-1333

An extension of the existing explanation of the flow mechanisms characteristic of the wing-Gurney flap flow has been proposed. Based on the Helmholtz vortex theory, it has been postulated at the onset of the present study that, in addition to the spanwise vortices, as predicted by a commonly accepted flow hypothesis one or more pairs of streamwise trailing vortices ought to exist. A series of wind-tunnel models, including a clean wing and one full-span and two partial-span Gurney flaps, have been tested in a low-speed wind tunnel. Several techniques, including two methods of flow visualization of trailing vortices and measurements of rotational speeds produced by these vortices, have been employed. All of these methods have consistently and clearly indicated the presence of additional vortices. As such, these vortices are important for accurate prediction of the aerodynamic characteristics of wing-Gurney flap configurations.

Nikolic, V. R.

"MOVABLE TIP STRAKES AND WING AERODYNAMICS"

Journal of Aircraft, Vol. 42, No. 6, Nov.-Dec. 2005, pp. 1418-1426

A wind-tunnel study of the effects of the addition of movable tip strakes on the aerodynamic characteristics of a rectangular wing model has been conducted. This is a new application of the strake concept for modifying the flowfield around a wing. The addition of sharp-edged slender delta-wing-shaped strakes significantly modified the flow pattern in the vicinity of the wing through generation of vortex lift. The strakes improved the lift-to-drag ratio of the baseline wing by as much as 23%. The method can have potential for lateral control too. Based on limited flow-visualization results, it appears that the strakes favorably influence the near-field roll up of the wing trailing vortices. The approach warrants additional investigation using more advanced measurement and flow-visualization techniques.

Nikolic, V. R.

"EFFECT OF GURNEY FLAP RELATIVE SPAN ON LIFT, DRAG, AND TRAILING VORTEX OF A RECTANGULAR WING"

AIAA Paper No. 2007-4177, Miami, FL, June 200.

An experimental study has been conducted to examine the effects that Gurney flap span has on the lift and drag of the wing-flap configuration and the near-field trailing vortex strength. The configurations tested included a rectangular wing, a full-span Gurney flap and two Gurney flaps having spans equal to one half the wing span, one positioned outboard, and the other inboard. All three flaps had a height equaling six percent of the wing chord. As expected, all three flaps significantly changed the wing lift and drag characteristics. While the flapped configurations developed much higher both lift

and drag coefficients, the overall effect on the wing lift-to-drag ratio has been found to be detrimental for all three flap configurations as compared to the baseline wing, the negative effect increasing with the flap span. Also, significant flattening of the lift-to-drag vs. lift coefficient curve has been observed. As expected, the addition of the flaps led to additional trailing vortices which affect the overall trailing vortex rollup and strength. The effect of the flaps on the trailing vortex strength in the near field has been quantified using a rollup tightness factor. This measure has indicated that while the configurations employing the full-span Gurney flap and the 50-percent-span flap located over the outboard wing sections exhibited trailing vortex strength reductions over most of the range of angles of attack tested, the configuration involving the inboard 50-percent flap developed stronger trailing vortices in the near field. These results have indicated that an effective means for trailing vortex reduction via Gurney flap use should be sought within the design space incorporating flaps located outboard. Future studies should include outboard Gurney flaps of varying relative span, other wing planforms and higher Reynolds numbers. Also, far field effects need to be examined.

Nikolic, V. R.

"PLANFORM VARIATIONS AND AERODYNAMIC EFFICIENCY OF MOVABLE TIP STRAKES"

Journal of Aircraft, Vol. 44, No. 1, January-February 2007, pp. 340-343

The movable tip strake represents a novel use of the renowned concept believed to be important to the design of future airplanes. An experimental study has been conducted to explore the effects of varying strake planform on the performance of a rectangular wing. Four strake configurations, including two delta types, then one modified delta having a portion of the leading edge curved, and one cropped double delta, have been tested in a low-speed wind tunnel. The strakes were held at a constant setting relative to the main wing. The results showed noticeable advantages of the configurations employing strakes over the baseline wing. All strakes produced higher lift and drag coefficients than the clean wing. Future plans include extensive use of flow visualization to aid in better understanding the flow phenomena associated with these types of configurations. Effects on wake vortex attenuation and possible use in roll control should also be addressed.

Nikolic, V. R.

"EXAMINING A FAMILY OF MOVABLE WING TIP STRAKES INVOLVING VARYING LEADING EDGE FORMS AND SWEEP ANGLES"

AIAA Paper No. 2007-1270, Reno, NV, January 2007

The study constitutes an attempt to expand the understanding of an innovative use of a famous concept -- the use of movable wing tip strakes -- beyond the limited results of a previous exploratory investigation. It is believed that this novel method is significant to the design of airplanes in the future in several areas. Nine different configurations of movable wing tip strakes have been studied in a low-speed wind tunnel in combination with a rectangular wing model. The strakes varied in planform shape and they included four half-delta planforms, one planform whose leading edge combined a swept

straight line and a curved profile, and four configurations involving cropped double-delta planforms. All nine strakes featured sharp leading edges. The addition of the tip strakes significantly and consistently altered the aerodynamic characteristics of the wing. It has been found that one among the cropped double-delta tip strakes is most effective, in terms of lift-to-drag ratios at constant lift, to the other eight configurations, all of them being superior to the baseline wing over significant ranges of angle of attack. The cropped double-delta strake improved the aerodynamic efficiency of the baseline wing over a substantial range of moderate angles of attack by as much as 26 percent at the neutral setting. When deflected relative to the main wing, in the negative or positive sense, the strake improved the wing aerodynamic efficiency at higher or lower angles of attack, respectively.

Nikolic, V. R. and Jumper, E. J.

"FIRST LOOK INTO EFFECTS OF DISCRETE MIDSPAN VORTEX INJECTION ON WING PERFORMANCE"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1177-1182

The effects of midspan discrete vortex injection on the performance of a rectangular wing model were studied in a wind tunnel. Based on this preliminary study, discrete vortex injection, while affecting the wing lift and drag, does not degrade its overall performance to any significant degree. This is particularly so in the high-angle-of-attack range where use of vortex injection for wake turbulence alleviation had been proposed. The investigation confirms and expands previously reported, computationally determined results. This study was of a limited scope; additional aspects of discrete vortex injection warrant investigation.

Nikolic, V. R. and Jumper, E. J.

"ATTENUATION OF AIRPLANE WAKE VORTICES BY EXCITATION OF FAR-FIELD INSTABILITY"

AIAA Paper 1993-3511, Monterey, CA, August 1993

This paper presents the results of a computational study of the injection of discrete vortices at a wake-generating wing and their effect on the development and dynamics of the wing's wake. The study was motivated by the results of an experimental study by Rossow showing that injection of vortices at approximately the mid semispan of an airplane wing greatly reduced the potential hazard to an aircraft penetrating the wake. Our study suggests that the reduction in wake hazard is due to the excitation of the Crow instability in the primary 'wing-tip' vortices due to their interaction with secondary vortices formed around the injected vortices.

Nikolic, V. R., Jumper, E. J. and Nelson, R. C.

"MODIFIED, DISCRETE-VORTEX METHOD FOR STUDYING WING-LOADING EFFECTS ON WAKE DYNAMICS"

J. Aircraft, Vol. 33, No. 1, January-February 1996, pp. 155-16.

An inviscid model for calculating the roll up of wing-generated, vortical wakes has been developed. The model is shown to be an efficient means of studying the dynamics of the wake in the region from just behind the wing to the pre-viscous-dissipation far field. The model is based on a modified discrete-vortex method that includes the near-wing effects of the wing-bound vorticity and the fact that the wake originates at the wing, rather than at minus infinity. Three-dimensional wakes are produced by connecting the two-dimensional wake contours at successive Trefftz planes. The inclusion of the near-wing effects is shown to have a relatively large influence on the wake's dynamics and final disposition. The inclusion of rotational cores is shown to aid in smoothing the wake roll up, but appears to have little effect on the wake's final dispersion radii.

Ning, S. A.

"AIRCRAFT DRAG REDUCTION THROUGH EXTENDED FORMATION FLIGHT"

PhD Thesis, August 2011, Stanford University, Stanford, CA.

While the early pioneers of flight looked to birds to learn how to fly, the early aerodynamicists looked to birds to learn how to fly more efficiently. Among the many insights gleaned from nature, was the observation that migratory birds often flew together in formation. As aerodynamic theory developed, it was shown that formation flight could be used to increase range. Despite an understanding of the physics, technological challenges have prevented aviation from benefitting from the energy left behind in an aircraft's wake. However, advances in precision navigation and control over the last few decades have brought renewed attention to formation flight of aircraft. Past published studies have focused on close formation flight, but the hazards of flying in close proximity are unacceptable in commercial aviation. This research explores a more practical approach, which we term extended formation flight. Extended formations take advantage of the persistence of cruise wakes and extend the streamwise spacing between the aircraft by at least five wingspans. Classical aerodynamic theory suggests that the total induced drag of the formation should not change as the streamwise separation is increased, but the large separation distances of extended formation flight violate the simple assumptions of these theorems. At large distances, considerations such as wake rollup, atmospheric effects on circulation decay, and vortex motion become important. This dissertation first examines the wake rollup process in the context of extended formations and develops appropriate physics-based models. These simple models compare well with higher-fidelity Navier-Stokes solutions, as well as with experimental data. The wake model is then used to investigate the induced drag savings of formations of aircraft in the presence of uncertainty in model parameters, variation in atmospheric properties, and limitations of positioning accuracy. Extended formation flight is found to only be practical in low to moderately low turbulence conditions with streamwise separation distances less than about 40 to 50 wingspans. Tracking error is found to be the largest source of variation in the induced drag savings. At typical conditions, a 2-aircraft formation achieves a maximum reduction in induced drag of approximately 30 +/- 3%, while a 3-aircraft formation achieves a maximum reduction of 40 +/- 6% (95% confidence intervals). High-fidelity analyses are utilized to help understand the impact of compressibility while flying in formation. An Euler solver is modified to allow the use of the wake vortex model. This solver is then used to analyze the inviscid aerodynamic forces and moments of transonic wing/body configurations flying in a 2-aircraft extended formation. By slowing down by about 2%, a formation can

achieve large induced drag reductions with little compressibility penalties. Flying further from the center of the vortex can allow for slightly higher cruise speeds in exchange for higher induced drag. Finally, the methodology is applied to studying formations of non-identical aircraft. Fundamental considerations in optimally arranging the formations are identified. Choosing a proper formation arrangement can have a significant impact on the fuel burn. Simple guidelines for choosing the arrangement of the formation are found to often coincide with the optimal arrangement. Re-arranging the formation enroute, to minimize fuel burn, is shown to be generally unnecessary, and even in the best cases can only provide fuel savings on the order of half a percent.

Ning, S. A. and Kroo, I.

"COMPRESSIBILITY EFFECTS OF EXTENDED FORMATION FLIGHT"

AIAA Paper No. 2011-3812, June 2011, Honolulu, Hawaii.

Aircraft flown in formations may realize significant reductions in induced drag by flying in regions of wake upwash. However, most transports fly at transonic speeds and compressibility effects in formation flight are not well understood. This study uses an Euler solver to analyze the inviscid aerodynamic forces and moments of transonic wing/body configurations flying in a 2-aircraft formation. We consider formations with large streamwise separation distances (10-50 wingspans) in an arrangement we term extended formation flight. Compressibility-related drag penalties in formation flight may be eliminated by slowing 2-3 percent below the normal out-of-formation drag divergence Mach number, at fixed lift coefficient or fixed altitude. The latter option has the additional benefit that the aerodynamic performance of the formation improves slightly at higher lift coefficients. Optimal in-formation lift coefficients are not nearly as high as those estimated by incompressible analyses, but if not limited by engine performance, modest increases in altitude can yield further improvements in aerodynamic efficiency. Increasing the lateral separation of the aircraft can allow for slightly higher cruise speeds in exchange for higher induced drag. For the configurations examined here, a 1-2 percent reduction in Mach number combined with a lateral spacing increase of 5 percent span achieves a total formation drag savings of about 10 percent.

Ning, S. A. and Kroo, I.

"MULTIDISCIPLINARY CONSIDERATIONS IN THE DESIGN OF WINGS AND WING TIP DEVICES"

Journal of Aircraft, Vol. 47, No. 2, March-April 2010, pp. 534-543.

Conceptual wing design analysis methods are combined with numerical optimization to find minimum-drag wings subject to constraints of lift, weight, pitching moment, and stall speed. Tip extensions and winglets designed for minimum drag achieve similar performance, with the optimal solution depending on the ratio of the maneuver lift coefficient to the cruise lift coefficient. The results highlight the importance of accounting for the depth of the wing structural box in the weight model and including constraints on stall speed. For tailless aircraft, C-wings show a slight performance advantage over wings with winglets when longitudinal trim and stability constraints are considered.

This performance advantage is more significant for span-constrained or low-sweep designs. Finally, to demonstrate other possible applications of the method, planer wings with active load alleviation are optimized, showing drag savings on the order of 15 percent.

Ning, S. A., Flanzer, T. C. and Kroo, I. M.

"AERODYNAMIC PERFORMANCE OF EXTENDED FORMATION FLIGHT"

Journal of Aircraft, Vol. 48, No. 3, May-June 2011, pp. 855-865.

The aerodynamic benefits of formation flight have been known for nearly a century. However, these benefits have yet to be realized in a commercial environment in part due to the hazards associated with close formation flight. This paper explores a more practical approach to formation flight called extended formation flight, which takes advantage of the persistence of cruise wakes and extends the streamwise spacing between the aircraft by at least 10 spans. Induced-drag savings are estimated in an incompressible analysis considering the effects of wake rollup, vortex decay, vortex instabilities, vortex motion, atmospheric turbulence and stratification, and stochastic behavior. Extended formations are found to be unpractical for streamwise spacings larger than about 40 spans between each aircraft. For spacings around 10 to 40 spans, with low to moderately low atmospheric turbulence, a two-aircraft formation has a maximum induced-drag reduction of 30 +/- 3%, while a three-aircraft formation has a maximum induced-drag reduction of 40 +/- 6%. At these distances, aircraft tracking error is the most significant contribution to the variation in drag savings. Studies of transonic effects, ride quality concerns, and control and sensing strategies are necessary to further evaluate the potential of extended formation flight.

Ning, S. A., Flanzer, T. C. and Kroo, I. M.

"AERODYNAMIC PERFORMANCE OF EXTENDED FORMATION FLIGHT"

AIAA Paper No. 2010-1240, January 2010, Orlando, FL.

Close formation flight is of limited practicality for commercial aviation. Our concept of extended formation flight takes advantage of the persistence of cruise wakes by extending the streamwise spacing between aircraft in a formation. This allows the aircraft to fly at safe separation distances from each other, while still benefiting from the upwash of the upstream wake(s). In this paper we are interested in estimating the performance of these extended formations, and estimating some of the effects that limit the longitudinal extent of the formation. We consider the effects of wake rollup, vortex decay, vortex instabilities, vortex motion, and atmospheric turbulence and stratification in an incompressible analysis. Formations consisting of two and three aircraft are examined. For each we evaluate the mean formation induced drag savings and associated uncertainties. At separation distances less than 20 spans, a two aircraft formation saves 26-31 percent in induced drag, while a three aircraft formation saves 38-45 percent in induced drag. Aircraft tracking error, and vortex motion due to turbulent gusts are the greatest contributors to the variation in drag savings. Extended

formations are likely only practical in low to moderately low turbulence levels and for streamwise spacings less than about 50 spans.

Ning, S. A., Kroo, I., Aftosmis, M. J., Nemec, M. and Kless, J. E.

"EXTENDED FORMATION FLIGHT AT TRANSONIC SPEEDS"

Journal of Aircraft, Vol. 51, No. 5, September-October 2014, pp. 1501-1510.

Aircraft flown in formations can realize significant reductions in drag by flying in regions of wake upwash. However, most transports fly at transonic speeds where the impact of compressibility on formation flight is not well understood. This study uses an Euler solver to analyze the inviscid aerodynamic forces and moments of transonic wing/body configurations flying in a two-aircraft formation. Formations with large streamwise separation distances (10-50 wingspans) are considered. This work indicates that compressibility-related drag penalties in formation flight may be eliminated by slowing 2-3 percent below the nominal out-of-formation cruise Mach number, either at fixed lift coefficient or fixed altitude. The latter option has the additional benefit that the aerodynamic performance of the formation improves slightly at higher lift coefficients. Although optimal information lift coefficients are not as high as those estimated by incompressible analyses, modest increases in altitude can yield further improvements in aerodynamic efficiency. Increasing the lateral separation of the aircraft allows for slightly higher cruise speeds in exchange for higher induced drag. For the configurations examined here, a 1-2 percent reduction in Mach number combined with a lateral spacing increase of 5 percent span (vertical spacing aligned with the vortex) achieves a total formation drag savings of about 10 percent.

Ning, Z. and Yang, Z.

"AN EXPERIMENTAL INVESTIGATION ON THE CONTROL OF TIP VORTICES FROM WIND TURBINE BLADE"

AIAA Paper 2013-1104, January 2013, Grapevine, TX.

Wind turbine dynamics, wake effects and environmental impacts have been identified the most significant research topics needed for wind resource characterization and wind power generation. Among these issues, tip vortices generated from the blade tip have been recognized as a substantial resource for the turbulent wake flow as well as the aerodynamic noise emission from a wind turbine. An experimental study is conducted to characterize the evolution of the tip vortices downstream a well-designed horizontal axis wind turbine (HAWT) model. In addition to measuring dynamic wind loads (both aerodynamic forces and moments) and power output from the wind turbine model, a Particle Image Velocimetry (PIV) system is used to make phase-locked flow field measurements to quantify the time-evolution of the wake vortex and turbulence flow structures downstream of the wind turbine model. The objective of this study is to find an effective way to restrict the development of tip vortices and thus the consequential noise emission. By altering the blade tip design, unwanted tip vortices and vibration of blade is suppressed considerably. The detailed flow measurements at several cross sections of the blade are also conducted to illuminate the mechanism of vorticity reduction. The detailed flow

field measurements are correlated with the wind load and power output measurements to elucidate the underlying physics associated with power generation and environmental impacts from wind turbines.

Nixon, D.

"FAR FIELD EFFECTS OF WING WAKES"

AIAA Paper No. 2007-1268, Reno, NV, January 2007

This paper is concerned with the derivation of the equation for vehicle drag in terms of information available in the wake. Although the classic result for drag can be obtained by the analysis if the far field pressure is assumed to return to freestream values there is some doubt as to its validity. Also, the general assumption that drag represented by entropy production is not related to drag due to lift seems to be untrue. Furthermore, it was found that there is a residual effect of the aircraft left in the atmosphere that can cause disturbances to following aircraft. It is also found that the boundary condition for the Navier Stokes equations far downstream of the aircraft is that the shear stresses are zero.

Nolan, D. S.

"THE STABILIZING EFFECTS OF AXIAL STRETCHING ON TURBULENT VORTEX DYNAMICS"

Physics of Fluids, Vol. 13, No. 6, June 2001, pp. 1724-1738.

The evolution and dynamics of vortices in inviscid, incompressible flow under the influence of a deformation field which causes stretching in the axial direction are studied. These vortices are simulated using three-dimensional vortex methods which offer the advantages of having no inherent numerical dissipation and great computational efficiency for short to intermediate times. Two cases are studied: The evolution of a stable, but strongly perturbed vortex, and the evolution of an unstable vortex. In both types of vortices, it is found that the stretching and radial inflow associated with the surrounding deformation field can suppress the growth of disturbances and slow the development of turbulence. This stabilization is even greater than what one would expect from the purely kinematic effects of the deformation field alone, indicating there is negative feedback on the nonlinear vortex dynamics. The physical mechanisms for stabilization by stretching are discussed, along with potential applications for understanding the stability of intense geophysical vortices maintained by convection.

Nomura, K. K., Tsutsui, H., Mahoney, D. and Rottman, J. W.

"SHORT-WAVELENGTH INSTABILITY AND DECAY OF A VORTEX PAIR IN A STRATIFIED FIELD"

J. Fluid Mech., Vol. 553, 2006, pp. 283-322

The evolution of a counter-rotating vortex pair in a stably stratified fluid is investigated using direct numerical simulations. The study focuses on the short-wavelength elliptic instability occurring in this

flow and the subsequent decay of the vortices. Depending on the level of stratification, as characterized by the Froude number which indicates the time scale of buoyancy to that of the instability, and the stage of evolution, stratification effects may significantly alter the behavior of the flow. In the case of weak to moderate stratification, the elliptic instability develops qualitatively in the same manner as in unstratified fluid. The primary effect of stratification is to reduce the vortex separation distance which enhances the mutually induced strain. Consequently, the instability has an earlier onset and higher growth rate with increasing stratification. The behavior is essentially described by linear stability theory for unstratified flow if the varying separation distance is taken into account. On the other hand, the final breakdown and decay of the flow may be greatly modified by stratification since buoyancy effects eventually emerge after sufficient time has elapsed. The decay is enhanced owing to additional mechanisms not present in unstratified flow. Secondary vertical vortex structures form between the primary vortices promoting fluid exchange in the transverse direction. Detrainment of fluid from the primary vortices by the generated baroclinic torque also contributes to the more rapid breakdown of the flow. In the case of strong stratification, in which the time scale of buoyancy is comparable to that of the instability, the flow is significantly altered. As a result of strong baroclinic torque, the primary vortices are brought together and detrainment occurs earlier. The associated reduction in radii of the vortices results in a higher axial wave mode and a more complex radial structure of the instability. Detrainment and mixing accelerate their decay. Late time evolution is dominated by the successive generation of alternate signed baroclinic torque which results in an oscillation of the total flow circulation at the buoyancy frequency.

Noonkester, V. R., Richter, J. H. and Jensen, D. R.

"UNIQUE ECHOES OBSERVED BY FM-CW RADAR AT A JET AIRPORT"

TN 2787, September 1974, Naval Electronics Lab. Center, San Diego, CA

The capability of the recently developed FM-CW radar to detect detailed low-level small-scale humidity structure suggested the possibility that the radar may be capable of detecting wing-tip vortices. This report presents examples and describes statistical features of a unique echo observed by the FM-CW radar at the west end of runway 9-27 at the International Airport, Lindbergh Field, in San Diego. The data strongly indicate that the unique echo is created by departing aircraft. The source and nature of the echo is undetermined, however.

Nordstrom, J. and Lonn, B.

"ENERGY DECAY OF VORTICES IN VISCOUS FLUIDS: AN APPLIED MATHEMATICS VIEW"

Journal of Fluid Mechanics, Vol. 709, 2012, pp. 593-609.

The energy decay of vortices in viscous fluids governed by the compressible Navier-Stokes equations is investigated. It is shown that the main reason for the slow decay is that zero eigenvalues exist in the matrix related to the dissipative terms. The theoretical analysis is purely mathematical and based on the energy method. To check the validity of the theoretical result in practice, numerical solutions to

the Navier-Stokes equations are computed using a stable high-order finite difference method. The numerical computations corroborate the theoretical conclusion.

Nore, C., Bruno, A., Douady, S. and Abid, M.

"ON THE FEEDBACK OF VORTICITY ON STRETCHING"

Lecture Notes in Physics, Issue 555, 2000, pp. 275-282

In this paper, we have experimentally and numerically investigated the evolution of a vortex submitted to a non-uniform stretching. But it turns out that the vortex reacts by inducing secondary tori shaped structures which screen the effect of the primary stretching. This basically comes from the fact that there exists a differential rotation along the vortex axis which leads to a variation of the centrifugal force. The pressure gradient cannot balance this inhomogeneous centrifugal force anymore, the latter having a solenoidal part. Consequently, a secondary toroidal flow is induced which stretches the vortex in the regions where it was slowly rotating and compresses it where it was rapidly rotating.

Norman, T. R. and Light, J. S.

"ROTOR TIP VORTEX GEOMETRY MEASUREMENTS USING THE WIDE-FIELD SHADOWGRAPH TECHNIQUE"

AIAA Paper No. 1986-1780, June 1986, San Diego, CA.

Rotor tip vortex geometry data have been acquired using the wide-field shadowgraph technique. Shadowgraphs were taken of the wakes of two model main-rotor systems in hover. These shadowgraphs provided detailed tip vortex trajectories from which axial and radial vortex coordinates were measured. Another result of the experimental work was the development of a method to predict the degree of visibility of rotor tip vortices on shadowgraphs. Using this method, the ability of the shadowgraph technique to visualize tip vortices in the rotor wake was quantified.

Nosenchuck, D. M. and Brown, G. L.

"LIFTING BODY WITH REDUCED-STRENGTH TRAILING VORTICES"

US Patent 5,492,289, February 1996

A lifting body moves relative to a fluid, thereby creating a vortex field in the fluid downstream of the lifting body. The lifting body has a predetermined lift distribution along the length thereof which enhances the velocity component of the fluid flow directed outwardly from the centroid of the vortex field to reduce the strength of trailing vortices. In a preferred embodiment, the lifting body is a wing with a perturbation proximate to the tip end of the wing planform trailing edge.

Nosenchuck, D. M., Flannery, W. S. and Brown, G. L.

"CONTROL OF WING-TIP VORTICES"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 18-1 - 18-20

Experiments have been carried out which demonstrate the potential of using a redistribution of vorticity (through small changes in wing geometry) to affect significantly the core size of a wing-tip vortex. Prior to the experiments, the change in geometry which produced the increased core area was predicted using a numerical simulation and an optimization procedure.

Novak, F. and Sarpkaya, T.

"TURBULENT VORTEX BREAKDOWN AT HIGH REYNOLDS NUMBERS"

AIAA Journal, Vol. 38, No. 5, May 2000, pp. 825-834

This paper deals with vortex breakdown in noncavitating swirling flows in tubes at high Reynolds numbers. Breakdown in slender vortices of high intensity begins with a rapidly spinning spiral at a point dictated by the prevailing flow and boundary conditions. The nascent spiral bursts into turbulence shortly after its inception, i.e., the breakdowns occurring at relatively low gamma or Reynolds numbers are bypassed at sufficiently high Reynolds numbers. Additional findings concern the core bifurcation, the random reversals in the sense of the spiral windings, and the absence of a reversed-flow region. The core meandering and stagnation-point darting are quantified and discussed considering extensive velocity, turbulence, and spectrum measurements.

Novak, F. G.

"AN EXPERIMENTAL INVESTIGATION OF VORTEX BREAKDOWN IN TUBES AT HIGH REYNOLDS NUMBERS"

PhD Thesis, September 1998, Naval Postgraduate School, Monterey, CA.

This thesis deals with non-cavitating swirling flows with vortex breakdown in various tubes. Phenomenological and quantitative investigations were carried out at Reynolds numbers (Re) as high as 300,000. It was shown that a high Re vortex transitions to its new state (breaks down) via a rapidly spinning spiral form, as demonstrated with 4,000 frames per second video, short exposure time (6 ns) imaging, and Digital Particle Image Velocimetry. Of the known types, the spiral emerges as the fundamental breakdown form and the axisymmetric bubble may now be regarded as a relatively low Re occurrence that is bypassed at sufficiently high Re. Some new phenomena were observed at high Re: Extremely rapid spiral rotation (over 1,000 revolutions per second), core bifurcation, and changes in the sense of the spiral windings. Familiar features of breakdowns, such as the transition from a jet-like to wake-like axial velocity profile and the rapidly expanding vortex core, were observed in extensive time averaged velocity and turbulence results ascertained with Laser Doppler Velocimetry. However, a mean stagnation point and recirculation were absent in the highest Re flow. The core meandering and stagnation point darting in the turbulent flow field were quantified and discussed in detail.

Nuic, A., Poinot, C., Igaru, M., Gallo, E., Navarro, F. A. and Querejeta, C.

"ADVANCED AIRCRAFT PERFORMANCE MODELING FOR ATM: ENHANCEMENTS TO THE BADA MODEL"

24th Digital Avionics Systems Conference, Washington, DC, Oct-Nov 2005

An efficient Air Traffic Management (ATM) system requires planning of traffic flows that rely on accurate estimation of aircraft performances. New operational concepts, that will ensure seamless management of the forecasted growth of air traffic and provide increased capacity, are based on aircraft trajectory prediction. An aircraft performance model is the core of trajectory computation and therefore plays a central role in the development and evaluation of the future ATM systems.

Nybelen, L., Deniau, H., Boussuge, J.-F. and Schonfeld, T.

"SPATIAL SIMULATION OF A CO-ROTATING VORTEX MERGING PROCESS IN UNSTABLE CONDITIONS"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

The present numerical study is motivated by the challenge to simulate the three-dimensional spatial dynamics of a co-rotating vortex pair, through the development of an elliptic instability, using a high order solver of the compressible Navier-Stokes equations. This phenomenon was studied previously only by temporal simulations. The interest of spatial simulation is first to analyze the effect of the axial velocity on the merging process which are neglected with the temporal approach, and to study interaction with jet flows. The numerical problem is the choice of boundary conditions: for the inflow and outflow conditions as well as for the lateral boundary conditions to represent a fluid at rest. Indeed, for these boundary conditions the problem comes from the no-zero circulation of the vortex system considered. The classic boundary conditions of Poinot and Lele based on the characteristics wave approach have been modified to be more adapted to the physics considered here. This new boundary condition assumes an irrotational flow close to the borders (to determine the magnitude of the waves), as the vorticity field is concentrated on the computational domain center where the vortex system is initially placed. After a validation of these improved boundary conditions and of all numerical tools used such as selective artificial dissipation, two spatial simulations of the vortex breakdown phenomenon have allowed validating our solver for a three-dimensional case by comparison to the results of Ruith et al. Thus, the merging process of equal co-rotating vortices through the development of elliptic instability with axial velocity were simulated by 3D spatial simulations.

Nybelen, L., Moet, H. and Paoli, R.

"SIMULATIONS OF MERGING IN A TWO CO-ROTATING VORTEX SYSTEM"

European Conference on Computational Fluid Dynamics, TU Delft, The Netherlands, 2006

All aircraft shed, because of lift, a wake ('vorticity sheet') which rapidly rolls up into several concentrated vortices at a distance of a few chords behind the trailing edge of the wing. A simplified configuration has been adopted to understand the physical mechanisms characterizing the merging process in the extended near-field. This consists in two co-rotating and symmetric (i.e. same core size and circulation) vortices, corresponding to the two vortices generated at wing and flap tip, respectively. Both the Lamb-Oseen and the Jacquin VM2 vortex models were used as numerical initial conditions. Two dimensional direct Numerical Simulations (DNS) were first conducted at low Reynolds numbers to study the merging in stable conditions. A so-called convective stage is identified which is critical in the stable merging process. It starts when the ratio between the vortex core size and the separation distance of the two vortices reaches the critical value for the Reynolds numbers considered. It is known that the vortex system might experience an elliptic short wavelength instability during the merging process at high Reynolds numbers. A second set of three-dimensional simulations (DNS/LES) was then carried out to analyze the development of such a short wavelength instability. The development of the instability was analyzed by either looking at the flow topology or by tracking the energy spectrum of the system. The resulting (unstable) vortex has a two-scale tangential velocity profile as in the case of two-dimensional (stable) merging. However, the unstable merging is faster than the stable merging.

Nybelen, L., Paoli, R. and Chevalier, G.

"PREVIOUS WORK AND PRESENT KNOWLEDGE ON VORTEX INTERACTIONS WITH JETS AND WAKES"

AST4-CT-2005-012238, CERFACS, Toulouse, France, July 2005

Previous test campaigns (e.g., C-Wake and Airbus measurements) have demonstrated that jets can modify the wake structure significantly. In addition, the precise influence of the fuselage wake and the wakes of different wing elements (e.g., engine nacelle, landing gear) is still not well understood and the present knowledge is not systematic. Two types of strategies are pursued in this work. On the one hand, progressively more and more realistic flow fields are treated, while on the other hand continuing to use a fundamental approach, e.g., single vortex/cold jet, vortex pairs/cold jet, single vortex/hot jet. The motivation for the fundamental approach is to identify the main effects and relevant parameters associated with the interactions of vortices with wake flows and with cold or hot jets. On the other hand, fluctuating jets or wakes may also represent means to act on the flow. A further goal is therefore to evaluate the impact of such perturbations on wake vortices, and to determine whether pulsating jets or small devices, such as bluff bodies, could become an efficient way to act on the evolution of aircraft wakes and have an influence on vortex decay.

Nykl, S., Mourning, C., Ghandi, N. and Chelberg, D.

"A FLIGHT TESTED WAKE TURBULENCE AWARE ALTIMETER"

ISVC 2011, Part II, 2011, pp. 219-228.

A flying aircraft disturbs the local atmosphere through which it flies creating a turbulent vortex at each wing tip known as a wake vortex. These vortices can persist for several minutes and endanger

other aircraft traversing that turbulent airspace; large vortices are essentially invisible horizontal tornadoes and are a grave threat to smaller aircraft, especially during landing and take-off. Accidents related to wake turbulence have resulted in both loss of life and aircraft destruction in the United States and around the world. Currently no cockpit instrumentation exists that tracks wake vortices and enables a pilot to sense and avoid wake turbulence in real-time. This paper presents a prototype of a novel, flight tested instrument that tracks wake vortices and presents this information to a pilot in real time using a synthetic virtual world augmented with wake turbulence information.

Obabko, A. V. and Cassel, K. W.

"NAVIER-STOKES SOLUTIONS OF UNSTEADY SEPARATION INDUCED BY A VORTEX"

J. Fluid Mech., Vol. 465, 2002, pp. 99-130

Numerical solutions of the unsteady Navier-Stokes equations are considered for the flow induced by a thick-core vortex convecting along a surface in a two-dimensional incompressible flow. The presence of the vortex induces an adverse streamwise pressure gradient along the surface that leads to the formation of a secondary recirculation region followed by a narrow eruption of near-wall fluid in solutions of the unsteady boundary-layer equations. The locally thickening boundary layer in the vicinity of the eruption provokes an interaction between the viscous boundary layer and the outer inviscid flow. Numerical solutions of the Navier-Stokes equations show that the interaction occurs on two distinct streamwise length scales depending upon which of three Reynolds-number regimes is being considered. At high Reynolds numbers, the spike leads to a small-scale interaction; at moderate Reynolds numbers, the flow experiences a large-scale interaction followed by the small-scale interaction due to the spike; at low Reynolds numbers, large-scale interaction occurs, but there is no spike or subsequent small-scale interaction. The large-scale interaction is found to play an essential role in determining the overall evolution of unsteady separation in the moderate-Reynolds-number regime; it accelerates the spike formation process and leads to formation of secondary recirculation regions, splitting of the primary recirculation region into multiple corotating eddies and ejections of near-wall vorticity. These eddies later merge prior to being lifted away from the surface and causing detachment of the thick-core vortex.

Oberleithner, K., Paschereit, C. O., Seele, R. and Wygnanski, I.

"FORMATION OF TURBULENT VORTEX BREAKDOWN: INTERMITTENCY, CRITICALITY, AND GLOBAL INSTABILITY"

AIAA Journal, Vol. 50, No. 7, July 2012, pp. 1437-1452.

This study provides quantitative insight into the formation of vortex breakdown and the onset of global instability in a turbulent swirling jet. A water jet is guided through a rotating honeycomb that imparts the rotational motion passed through a contraction, and discharged into a large water tank. The flow states evolving at increasing swirl are mapped out via time-resolved particle image velocimetry. The experimental results scale properly with the swirl number based on the axial

momentum flux when the commonly used boundary-layer approximations are omitted. The instantaneous velocity field reveals that vortex breakdown occurs intermittently at a wide range of swirl numbers before it appears in the mean flow. At this intermittent state, the evolving breakdown bubble oscillates heavily between two streamwise locations where the vortex core is subcritical. Upon further increasing the swirl, the breakdown oscillations decay and a region of reversed flow appears in the mean flowfield. The formation of this so-called axisymmetric breakdown state is accompanied by a supercritical-to-supercritical transition of the inflowing vortex core. The reversed flow region is found to grow linearly with increasing swirl until the flow undergoes a supercritical Hopf bifurcation to a global single-helical mode, and vortex breakdown adopts a spiral shape. The global mode shape is extracted from the particle image velocimetry snapshots by means of proper orthogonal decomposition and Fourier analysis. The present experiment reveals that, at gradually increasing swirl, the jet first transitions to an axisymmetric breakdown state that remains globally stable until a critical swirl number is exceeded. This sequence of flow states agrees well with the transient formation of vortex breakdown observed in laminar flows.

Oberleithner, K., Sieber, M., Nayeri, C. N., Paschereit, C. O., Petz, C., Hege, H.-C., Noack, B. R. and Wygnanski, I.

"THREE-DIMENSIONAL COHERENT STRUCTURES IN A SWIRLING JET UNDERGOING VORTEX BREAKDOWN: STABILITY ANALYSIS AND EMPIRICAL MODE CONSTRUCTION"

Journal of Fluid Mechanics, Vol. 679, 2011, pp. 383-414.

The spatio-temporal evolution of a turbulent swirling jet undergoing vortex breakdown has been investigated. Experiments suggest the existence of a self-excited global mode having a single dominant frequency. This oscillatory mode is shown to be absolutely unstable and leads to a rotating counter-winding helical structure that is located at the periphery of the recirculation zone. The resulting time-periodic 3D velocity field is predicted theoretically as being the most unstable mode determined by parabolized stability analysis employing the mean flow data from experiments. The 3D oscillatory flow is constructed from uncorrelated 2D snapshots of particle image velocimetry data, using proper orthogonal decomposition, a phase-averaging technique and an azimuthal symmetry associated with helical structures. Stability-derived modes and empirically derived modes correspond remarkably well, yielding prototypical coherent structures that dominate the investigated flow region. The proposed method of constructing 3D time-periodic velocity fields from uncorrelated 2D data is applicable to a large class of turbulent shear flows.

O'Brien, J. M., Young, T. M., O'Mahoney, D. C. and Griffin, P. C.

"HORIZONTAL AXIS WIND TURBINE RESEARCH: A REVIEW OF COMMERCIAL CFD, FE CODES AND EXPERIMENTAL PRACTICES"

Progress in Aerospace Sciences, Vol. 92, 2017, pp. 1-24.

A review of wind turbine aerodynamics research is presented. The review is limited to Horizontal Axis Wind Turbine (HAWT) investigations. The focus is on recent near wake experiments, wake predictions by commercial CFD codes and current FSI and structural modelling attempts. For the near wake, the review considers experiments carried out in controlled conditions whereby the incoming freestream is perpendicular to the rotor plane. Additional anomalies such as wind shear, gusts and yaw transition are not considered. The survey of 3D commercial codes is also focused on HAWT models in parallel flow conditions. Finally, the structural models reviewed are divided into two separate categories: 1) blade deflection and performance under aerodynamic loads, and 2) the vibrational response of blades under aerodynamic loading. The aim is to highlight common trends within near wake experiments and investigate both CFD and FE modeling strategies -- to identify current limitations and future opportunities within the sector.

O'Bryan, T. C.

"AN EXPERIMENTAL STUDY OF THE EFFECT OF DOWNWASH FROM A TWIN-PROPELLER VTOL AIRCRAFT ON SEVERAL TYPES OF GROUND SURFACES"

NASA TN D-1239, NASA Langley, Langley Air Force Base, VA, January 1962

A full-scale, twin propeller VTOL aircraft with a maximum gross weight of 3,400 pounds has been operated on the ground to study the effect of downwash on several types of ground surfaces. Static operation over loose snow indicated a zone of obliterated vision ahead of the pilot in an arc of approximately 10 degrees on each side of the plane of symmetry. Static operation in the presence of loose surface material indicated that the downwash cleared the area near the aircraft of these particles without recirculation or damage to any components. Short-time operation at moderate forward speed over loose gravel, with the thrust axis at an angle of 70 degrees from the horizontal, resulted in propeller-blade erosion and numerous small dents and fabric punctures in the sides of the fuselage.

O'Bryan, T. C.

"AN INVESTIGATION OF THE EFFECT OF DOWNWASH FROM A VTOL AIRCRAFT AND A HELICOPTER"

NASA TN D-977, NASA Langley, Langley Air Force Base, VA, August 1961

Dynamic-pressure measurements, in ground effect, have been obtained about a single-rotor helicopter and a dual-propeller VTOL aircraft. The results indicate that the slipstream dynamic pressure along the ground, some distance from the center of rotation, is not a function of disk loading but merely a function of the gross weight or thrust of the aircraft. Furthermore, for a given gross weight the thickness of this outward flowing sheet of air is less for a small-diameter propeller (higher disk loading propeller).

O'Callaghan, J. J.

"FLIGHT CONTROL AND WAKE TURBULENCE EFFECTS ON AMERICAN AIRLINES FLIGHT 587"

AIAA Paper 2005-6110, August 2005, San Francisco, CA.

On November 12, 2001, American Airlines flight 587, an Airbus Industrie A300-600, was destroyed when it crashed into a residential area of Belle Harbor, New York, shortly after takeoff from runway 31L at John F. Kennedy International Airport. Before impact, the vertical stabilizer, rudder, and left and right engines departed the airplane. The 2 pilots, 7 flight attendants, 251 passengers, and 5 persons on the ground were killed. The NTSB determined that the probable cause of the accident was the in-flight separation of the vertical stabilizer as a result of the loads beyond ultimate design that were created by the first officer's unnecessary and excessive rudder pedal inputs, and that contributing to these rudder pedal inputs were characteristics of the Airbus A300-600 rudder system design and elements of the American Airlines Advanced Aircraft Maneuvering Program. During the investigation, it was determined that the airplane had encountered wake turbulence from a Boeing 747 at the time the first officer made his rudder pedal inputs. An objective of the investigation was to determine the significance of both the first officer's rudder inputs and the wake turbulence to the subsequent airplane dynamics and buildup of aerodynamic loads on the vertical tail. Simulations of the airplane motion, driven by the thrust and flight control inputs recorded on the Flight Data Recorder (FDR), as well as external wind gusts and pitch, roll, and yaw moments required to match the airplane dynamics recorded by the FDR, were used to determine the relative contribution of the wake turbulence (represented by the external wind gusts and moments) and flight control inputs to the overall airplane motion. The results of the simulations indicate that the first officer's flight control inputs produced the buildup of the sideslip angle and aerodynamic loads on the vertical tail that caused it to separate from the airplane. The effect of the wake turbulence on the airplane motion was minor.

Ochi, Y. and Kominami, T.

"FLIGHT CONTROL FOR AUTOMATIC AERIAL REFUELING IN VORTEX WAKE BY TANKER"

Proceedings of the SICE Conference, 2005, pp. 1963-1966

This paper provides two design methods of a flight control system for aerial refueling. One is based on the proportional navigation guidance with acceleration control systems. The other employs the LOS (line-of-sight) angle control. Both control systems are designed using the model following servo controller. Computer simulation of aerial refueling in the presence of vortex wake by the tanker was conducted.

O'Connor, C. J. and Rutishauser, D. K.

"ENHANCED CAPACITY THROUGH REDUCTIONS IN SEPARATION: NASA'S AVOSS"

Journal of ATC, October-December 2001, pp. 4-10

An aspect of airport terminal operations that holds potential for efficiency improvements is the separation criteria applied to aircraft for wake vortex avoidance. These criteria evolved to represent safe spacing under weather conditions conducive to the longest wake hazards, and consequently are overly conservative during a significant portion of operations. Under many ambient conditions, such as

moderate crosswinds or turbulence, wake hazard durations are substantially reduced. To realize this reduction NASA has developed a proof-of-concept Aircraft VORtex Spacing System (AVOSS). Successfully operated in a real-time field demonstration during July 2000 at the Dallas Ft. Worth International Airport, AVOSS is a novel integration of weather sensors, wake sensors, and analytical wake prediction algorithms. Gains in airport throughput using AVOSS spacing as compared to the current criteria averaged 6%, with peak values approaching the theoretical maximum of 16%. The average throughput gain translates to 15-40% reductions in delay when applied to realistic capacity ratios at major airports.

O'Connor, C. J. and Rutishauser, D. K.

"ENHANCED AIRPORT CAPACITY THROUGH SAFE, DYNAMIC REDUCTIONS IN AIRCRAFT SEPARATION: NASA'S AIRCRAFT VORTEX SPACING SYSTEM (AVOSS)"

NASA TM-2001-211052, August 2001, NASA Langley Research Center, Hampton, V.

An aspect of airport terminal operations that holds potential for efficiency improvements is the separation criteria applied to aircraft for wake vortex avoidance. These criteria evolved to represent safe spacing under weather conditions conducive to the longest wake hazards, and are consequently overly conservative during a significant portion of operations. Under many ambient conditions, such as moderate crosswinds or turbulence, wake hazard durations are substantially reduced. To realize this reduction NASA has developed a proof-of-concept Aircraft VORtex Spacing System (AVOSS). Successfully operated in a real-time field demonstration during July 2000 at the Dallas Ft. Worth International Airport, AVOSS is a novel integration of weather sensors, wake sensors, and analytical wake prediction algorithms. Gains in airport throughput using AVOSS spacing is compared to the current criteria averaged 6%, with peak values approaching the theoretical maximum of 16%. The average throughput gain translates to 15-40% reductions in delay when applied to realistic capacity ratios at major airports.

O'Connor, E. J., Illingworth, A. J., Brooks, I. M., Westbrook, C. D., Hogan, R. J., Davies, F. and Brooks, B. J.

"A METHOD FOR ESTIMATING THE TURBULENT KINETIC ENERGY DISSIPATION RATE FROM A VERTICALLY POINTING DOPPLER LIDAR, AND INDEPENDENT EVALUATION FROM BALLOON-BORNE IN SITU MEASUREMENTS"

Journal of Atmospheric and Oceanic Technology, Vol. 27, October 2010, pp. 1652-1664.

A method of estimating dissipation rates from a vertically pointing Doppler lidar with high temporal and spatial resolution has been evaluated by comparison with independent measurements derived from a balloon-borne sonic anemometer. This method utilizes the variance of the mean Doppler velocity from several sequential samples and requires an estimate of the horizontal wind speed. The noise contribution to the variance can be estimated from the observed signal-to-noise ratio and removed where appropriate. The relative size of the noise variance to the observed variance provides a measure of the confidence in the retrieval. Comparison with in situ dissipation rates derived from the

balloon-borne sonic anemometer reveal that this particular Doppler lidar can retrieve dissipation rates over a range of at least three orders of magnitude. This method is most suitable for retrieval of dissipation rates within the convective well-mixed boundary layer where the scales of motion that the Doppler lidar probes remain well within the inertial subrange. Caution must be applied when estimating dissipation rates in more quiescent conditions. For the particular Doppler lidar described here, the selection of suitably short integration times will permit this method to be applicable in such situations but at the expense of accuracy in the Doppler velocity estimates. The two case studies presented here suggest that, with profiles every 4 s, reliable estimates of ϵ can be derived to within at least an order of magnitude throughout almost all of the lower 2 km and, in the convective boundary layer, to within 50 percent. Increasing the integration time for individual profiles to 30 s can improve the accuracy substantially but potentially confines retrievals to within the convective boundary layer. Therefore, optimization of certain instrument parameters may be required for specific implementation.

O'Connor, N.

"AIRCRAFT VORTEX SPACING SYSTEM (AVOSS) OVERVIEW AND FUTURE DIRECTION"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Several factors lead to a reduction in airport capacity in weather conditions that prevent the use of visual approach procedures. These factors include a reduction in the number of available runways and the longitudinal wake turbulence separation constraints used by Air Traffic Control (ATC). These wake constraints evolved over time to prevent wake encounters in weather conditions most conducive to long-lived wakes, and are unnecessarily large in weather domains that lead to rapid wake decay or drift away from the flight path. During visual conditions aircraft separation responsibility belongs to the pilots, who use their knowledge of weather conditions, lead aircraft type, and lead aircraft flight path to effectively self-separate from wake encounters. In many situations the resulting spacing is less than would be required in instrument operations. The AVOSS is designed to structure this process and minimize the difference in aircraft spacing between visual and instrument operations. The operational concept of AVOSS is to determine the spacing required to prevent wake vortex encounters, given the ambient weather conditions in existence at the airport. The AVOSS system uses sensed weather information to predict wake vortex behavior and develop safe spacing criteria. The meteorological subsystem uses sensors and modeling techniques to describe the vertical profiles of the wind, turbulence, and temperature from the surface to the glide slope intercept altitude. The wake predictor uses this weather profile and descriptions of the aircraft fleet at the airport to predict wake drift rate, sink rate, and decay rate for each modeled aircraft type. Runway throughput estimates are generated using the wake predictions. Wake sensors are used to check the predicted behavior. No ATC interface was included in the AVOSS demonstration. The AVOSS system was demonstrated at the Dallas Ft. Worth International airport in July of 2000. This paper will present an overview of the AVOSS as demonstrated. Included will be discussion of the system's potential impact on capacity and delays along with thoughts on the overall maturity of a Wake Vortex Advisory System (WVAS). A first generation WVAS is envisioned building on the success of the AVOSS. Such a system would offer

limited capability while allowing operational development. For example, an initial WVAS might be restricted to certain weather conditions. Development of a research effort leading to such a system is currently underway.

Odemark, Y. and Fransson, J. H. M.

"THE STABILITY AND DEVELOPMENT OF TIP AND ROOT VORTICES BEHIND A MODEL WIND TURBINE"

Experiments in Fluids, Vol. 54, 2013, pp. 1591-1 - 1591-16.

When designing new wind farms, one has to rely on models describing the flow field around and inside the farm, since direct numerical simulation is far too computationally expensive. To develop better models for power prediction of wind farms, knowledge about the flow field around turbines, the stability of the wakes and the interaction between them is essential. Since the conditions during field measurements are difficult to control, wind tunnel measurements play an important role when studying wakes behind wind turbines. Within the present work, an experimental methodology has been developed to study the evolution and stability of the tip vortices shed from the rotor blades of a small-scale turbine model. The stability of the tip vortices was studied by introducing a periodic disturbance to the flow, which is shown to have a clear effect on the development of the vortices. Prior to the vortex breakdown, clear signs of vortex pairing were also observed. A parameter study was performed by varying the amplitude and frequency of the forced disturbance, and the effect on the tip vortices was evaluated. This experiment is one of the first where the influence of a periodic disturbance on a wind turbine wake is studied, something that previously has been performed in several numerical studies.

O'Donnell, R. and Mohseni, K.

"MANIPULATION OF WING TIP VORTICES ON LOW ASPECT RATIO WINGS USING WINGLET CONTROL SURFACES"

AIAA Paper 2017-1270, January 2017, Grapevine, TX.

The aerodynamic forces generated by a wing tip mounted articulated winglet control surface on a low aspect ratio wing in steady flight are investigated. The wings experimentally tested constitute two categories, traditional trailing edge mounted aileron flaps, and wing tip mounted articulated winglets which hinge chordwise. Low-aspect-ratio (LAR) wings at low-Reynolds numbers were chosen because these parameters are common to micro aerial vehicle (MAV) flight. Control authority developed by the control surface configurations were directly compared by measuring lateral forces and specifically the roll moment in wind tunnel testing. Flat plate wing models were studied to isolate the low aspect ratio aerodynamics from more complicated wing geometry effects. The manipulation of wing tip vortices' (TV) by articulated winglets is found to be an effective method of generating roll, especially in sideslip situations. We see conventional flaps generate a predictable roll moment varying slightly with angle of attack while articulated winglets rely on altering the span-wise distribution of lift. It is seen that in the

delayed stall region, unique to LAR and delta wing flight, winglets generate the same authority as traditional flaps and develop greater authority in sideslip situations.

Oeseburg, F. and van Leeuwen, D.

"DISPERSION OF AERIAL AGRICULTURAL SPRAYS; MODEL AND VALIDATION"

Agricultural and Forest Meteorology, Vol. 53, Issue 3, January 1991, pp. 223-255

A model that has developed to calculate the dosages of airborne pesticides in the downwind area during aerial crop spraying. The model is valid for crosswind flying, small flying heights (~ 2m) and formulations consisting of an involatile pesticide or a combination of an involatile pesticide and a volatile carrier liquid (e.g. water). The model consists of two submodels: a model which describes the development of a pair of initial clouds, mainly owing to the action of the aircraft induced vortices, and a model which describes the atmospheric dispersion of this pair of initial clouds. The model was validated by means of the results of field experiments carried out by R. S. Crabbe and M. McMooye.

Oetzel, K. G. and Vallis, G. K.

"STRAIN, VORTICES, AND THE ENSTROPY INERTIAL RANGE IN TWO-DIMENSIONAL TURBULENCE"

Physics of Fluids, Vol. 9, No. 10, October 1997, pp. 2991-3004.

The properties of vortices in a strain field are used to construct a phenomenological theory of the enstrophy inertial range in two-dimensional incompressible turbulence. The theory, based in part on the results and behavior of numerical simulations, attempts to combine spectral inertial range theories of the Kolmogorov type with the dynamics of vortex interactions in physical space. It is based on the assumptions that coherent vortices can survive in a turbulent flow if of sufficient strength compared to the background straining field, and that coherent structures feel a mean strain field, independent of their scale. The first assumption is suggested by a result in the theory of uniform elliptic vortices, while the second comes from numerical simulations. The theory employs a single non-dimensional parameter, essentially the ratio between the enstrophy flux and the mean strain, which then characterizes flows from extremely intermittent decaying turbulence to nearly Gaussian passive scalar dynamics. The theory predicts that in forced two-dimensional turbulence, coherent structures reside in a 'background' straining field. The coherent vortices will dominate the flow at a sufficiently large scale, with a fairly abrupt transition at a small scale to a flow in which the classical $1/k$ enstrophy spectrum holds. In this classical region small amplitude vortices do not survive because the (large-scale) straining field is of larger amplitude than the (small-scale) vorticity.

O'Farrell, C. and Dabiri, J. O.

"PERTURBATION RESPONSE AND PINCH-OFF OF VORTEX RINGS AND DIPOLES"

Journal of Fluid Mechanics, Vol. 704, 2012, pp. 280-300.

The nonlinear perturbation response of two families of vortices, the Norbury family of axisymmetric vortex rings and the Pierrehumbert family of two-dimensional vortex pairs, is considered. Members of both families are subjected to prolate shape perturbations like those previously introduced to Hill's spherical vortex, and their response is computed using contour dynamics algorithms. The response of the entire Norbury family to this class of perturbations is considered, to bridge the gap between past observations of the behavior of thin-cored members of the family and that of Hill's spherical vortex. The behavior of the Norbury family is contrasted with the response of the analogous two-dimensional family of Pierrehumbert vortex pairs. It is found that the Norbury family exhibits a change in perturbation response as members of the family with progressively thicker cores are considered. Thin-cored vortices are found to undergo quasi-periodic deformations of the core shape, but detrain no circulation into their wake. In contrast, thicker-core Norbury vortices are found to detrain excess rotational fluid into a trailing vortex tail. This behavior agrees with previous results for Hill's spherical vortex, as well as with observations of pinch-off of experimentally generated vortex rings at long formation times. In contrast, the detraining of circulation that is characteristic of pinch-off is not observed for Pierrehumbert vortex pairs of any core size. These observations agree with recent studies that contrast the formation of vortices in two and three dimensions. We hypothesize that transitions in vortex formation, such as those occurring between wake shedding modes and in vortex pinch-off more generally, might be understood and possibly predicted based on the observed perturbation responses of forming vortex rings or dipoles.

Offi, D. L., Lewis, W. and Lee, T.

"DETECTION OF HAZARDOUS METEOROLOGICAL AND CLEAR-AIR PHENOMENA WITH AN AIR TRAFFIC CONTROL RADAR"

Proceedings International Conf., Institution of Electrical Engineers, Oct, 1982, pp. 316-320

An account is given of the modifications made in the Airport Surveillance Radar (ASR-8) test bed at the FAA Technical Center at Atlantic City Airport (N.J.). The modifications, arrived at by the FAA, the Wave Propagation Laboratory, and MIT's Lincoln Laboratory, were made to observe low-level wind shear and turbulence associated with both thunderstorms and aircraft trailing wake-vortices. The modifications, consisting of a second antenna system and a separate receiver and Doppler processing chain, used the standby channel of the radar for these measurements. The results obtained are summarized. In describing the system, it is noted that the 15-foot parabolic antenna is interconnected with the ASR-8, operating with a peak transmitter power of 1 MW, a frequency of 2.79 GHz, a pulse repetition rate of 1030/sec, and a pulse length of 0.6 microsec. The separate receiver and Doppler processing chain comprises in phase and quadrature detectors, analog/digital converters, and a minicomputer with associated peripherals.

Ogasawara, T., Misaka, T., Ogawa, T., Obayashi, S. and Yamada, I.

"MEASUREMENT OF AIRCRAFT WAKE VORTICES USING DOPPLER LIDAR"

J. Fluid Science and Technology, Vol. 3, No. 4, 2008, pp. 488-499

In this research, the wake turbulence from actual passenger airplanes taking off from Sendai airport was measured with Electronic Navigation Research Institute's Doppler laser radar (lidar). First, the influence of the surrounding wind on the behavior of wake vortices was investigated. The wake vortices in the crosswind case disappear more quickly from the runway than those of the low surrounding wind and head wind cases. In addition, the wake vortices in the case of large crosswind move faster than those in small crosswind. Next, the correction factor was estimated by using the pseudo lidar measurements based on Computational Fluid Dynamics. The corrected data for weak surrounding wind case agreed with the existing wake vortex model.

Oh, S. and Jung, S.

"EXPERIMENTAL STUDY ON THE NEAR FIELD STRUCTURE OF WING-TIP VORTEX"

AIAA Paper No. 2000-0792, Reno, NV, January 2000

The structure and development procedure of the wing-tip vortex in the near field of the downstream of the rectangular wing has been investigated. The experiments have been conducted with the wing with NACA 6409 airfoil cross-section. The flow field of the vortex was measured with a spherical type five-hole probe from $0.1c$ to $2.0c$ behind the trailing edge. Comparing with other experimental results using hot-wire system validates the results of current experiments. Through the experiments, the streamline patterns in the cross-flow plane confirm that the vortex flow is composed of inner viscous core, spiral out region, tightly wound spiral region, and the external potential vortex region. In addition, it is observed that the flow patterns in the potential vortex region show slight tendency of 'spiral in' characteristics. The tangential velocity components show similarity patterns and clear core region as studied previously, but the distribution of the axial velocity components provides more detailed information on the deformation procedure of the wing-tip vortex and shows some oscillation in magnitude. The maximum axial velocity at the vortex core is larger than that of the free stream, and decreasing in its magnitude with distance downstream, while the value of the averaged axial velocity in the vortex core region is still smaller than that of free stream velocity like other studies. The oscillation in the magnitude of the axial velocity around the vortex core region shows the similar characteristics of the shape of a hurricane. The total pressure and helicity distribution have been also studied to analyze the vortex structure. These properties show clear variation of the vortex structure, vortex core position, and its deformation in the near field. It has been also found that the vortex core structure is closely related between axial velocity and the tangential velocity components.

Ohanian, C., McCauley, G. J. and Savas, O.

"A VISUAL STUDY OF VORTEX INSTABILITIES IN THE WAKE OF A ROTOR IN HOVER"

Journal of the American Helicopter Society, Vol. 57, 2012, pp. 042005-1 to 042005-8.

A visual study of the instability characteristics of the helical vortex filaments trailing from the tips of a three-bladed lifting rotor in a water tank is presented. The rotor diameter was 25.4 cm, and its rotation rate ranged from 4 to 12 revolutions per second. Soon after their formation, the vortex filaments

developed long- and short-wave instabilities. In the long-wave instability mode, two of the three vortices coming off the rotor orbited around each other and merged in about 0.4 of the theoretical orbit time of equistrength two-dimensional vortices, after which the third vortex joined the merger to form a single, apparently turbulent helical vortex filament. The wavelengths of the short-wave instabilities were about 0.4 of the wake radius, about 17 cycles over the circumference. The short waves exhibited a linear growth rate during the first half of their orbital motion and an exponential growth prior to merging. The linear growth rate was about 0.0034 D/rad. The e-folding time for the exponential growth rate was about 0.52 rad.

Ohring, S. and Lugt, H. J.

"INTERACTION OF A VISCOUS VORTEX PAIR WITH A FREE SURFACE"

Journal of Fluid Mechanics, Vol. 227, 1991, pp. 47-70.

A vortex pair in a viscous, incompressible fluid rises vertically toward a deformable free surface. The mathematical description of this flow situation is a time-dependent nonlinear free-surface problem that has been solved numerically for a two-dimensional laminar flow with the aid of the Navier-Stokes equations by using boundary-fitted coordinates. For several selected flow parameters, results are presented on the decay of the primary vortices and their paths, the generation of surface vorticity and secondary vortices, the development and final stage of the disturbed free surface, and the influence of surface tension. High and low Froude numbers represent the two extremes of free-surface yielding and stiffness, respectively. For an intermediate Froude number, a special rebounding due to the presence of secondary vortices has been observed: the path of the primary vortex center portrays a complete loop.

Okada, S. and Hiraoka, K.

"EXPERIMENTAL STUDIES OF REDUCTION OF THE WING TIP VORTEX BY SUCTION"

AIAA Paper No. 2003-3533, Orlando, FL, June 2003

The wing tip vortex occurs in the wing tip neighborhood on an aircraft in flight, and cannot be avoided for three-dimensional wing. Then the induced drag is generated by the wing tip vortex. So, the reduction of the wing tip vortex is a very important problem for an aircraft. There are many studies of the wing tip vortex and the flow control techniques near the wing tip for the reduction of the wing tip vortex. However, there is little study of control of the wing tip vortex by suction. In this paper at first, the characteristics of the wing tip vortex were explained in detail by the low-speed wind tunnel experiments using the two-dimensional hot wire anemometer. Next, controlling the flow near the wing tip by suction and effects against the reduction of the wing tip vortex were investigated. Suction was carried out at various positions of the wing tip. Then it is shown that the wing tip vortex is decreased by appropriate suction and the amount of reduction is different according to suction points.

Okamoto, M. and Azuma, A.

"AERODYNAMIC CHARACTERISTICS AT LOW REYNOLDS NUMBERS FOR WINGS OF VARIOUS PLANFORMS"

AIAA Journal, Vol. 49, No. 6, June 2011, pp. 1135-1150.

The aerodynamic characteristics of various wing planforms at low Reynolds numbers (about 10,000) were studied by conducting wind-tunnel tests. These low Reynolds numbers correspond to the flights of small creatures, such as insects. Elliptical, rectangular, and triangular planforms with various aspect ratios were used in this study, as well as a swept rectangular (parallelogram) wing with an aspect ratio of four. The wing sections of all models were thin rectangular airfoils. The aerodynamic forces (lift and drag) and the pitching moment acting on the wing were measured for a wide range of angles of attack (including the maximum of 90 deg). Nonlinear characteristics of the lift coefficient were obtained, even at low angles of attack for high-aspect-ratio wings, whereas a small lift slope and a large maximum lift coefficient were obtained for low-aspect-ratio wings. The drag and the pitching moment coefficients also exhibited nonlinear characteristics. The effect of the Reynolds number based on the wing chord was comparatively small, but a distinctive phenomenon in low-Reynolds-number flow was observed in flow visualization using oil-film and smoke-wire methods.

Okamoto, S.

"VISUALIZATION OF IMPINGEMENT OF BROKEN-DOWN VORTEX ON TAIL"

Journal of Wind Engineering and Industrial Aerodynamics, Vol. 91, 2003, pp. 65-74.

The impingement of a streamwise vortex on a fin is investigated experimentally with high-image-density particle image velocimetry (PIV) and dynamic pressure transducers to relate the structure of vortex breakdown to the spectra of surface pressure along the fin. The instantaneous and ensemble-averaged distributions of vorticity from PIV show strong concentrations of vorticity along the edges of the breakdown region. Correspondingly, the amplitude response of the pressure spectra is the strongest when the fin is located near the edge of vortex breakdown. The dominant frequency of the surface pressure is insensitive to cross-stream displacements of the vortex axis relative to the leading edge of the fin. Spectra of surface pressure at crucial locations on the fin are related to these features of the instantaneous and averaged flow structure.

Okolo, W., Dogan, A. and Blake, W.

"EFFECT OF TRAIL AIRCRAFT TRIM ON OPTIMUM LOCATION IN FORMATION FLIGHT"

Journal of Aircraft, Vol. 52, No. 4, July-August 2015, pp. 1201-1213.

Aircraft flight generates vortices that induce nonuniform wind distribution in their wake. A trailing/follower aircraft will experience induced wind components and gradients with various magnitudes and directions, depending on its location relative to the leader. This paper explores two methods of determining the relative location for optimum formation flight, termed the sweet spot. The relative location with the highest lift-to-drag ratio on the follower is denoted as the static sweet spot. In

the second method, the trail aircraft is trimmed by adjusting the thrust and control surfaces to maintain its commanded position relative to the lead. The relative location requiring the least thrust is then assigned as the dynamic sweet spot. The results showed that, depending on the trail aircraft size, the static sweet spot might differ from the dynamic sweet spot. The effect of the leader weight and follower size on both static and dynamic sweet spot was also studied. It was discovered that the static and dynamic sweet-spot location changed when the size of the trail aircraft was modified. It was also observed that the static sweet spot remained the same but the dynamic sweet spot changed when the lead aircraft weight was modified.

Okolo, W., Dogan, A. and Blake, W.

"MODIFIED STUDY OF TRAIL AIRCRAFT TRIM EFFECT ON SWEET SPOT IN FORMATION FLIGHT"

AIAA Paper 2014-0541, January 2014, National Harbor, MD.

Aircraft flight generates vortices that induce nonuniform wind distribution in their wake. A trailing/follower aircraft will experience induced wind components and gradients with various magnitudes and directions, depending on its location relative to the leader. This paper explores two methods of determining the relative location for optimum formation flight, termed the sweet spot. The relative location with the highest lift-to-drag ratio on the follower is denoted as the static sweet spot. In the second method, the trail aircraft is trimmed by adjusting the thrust and control surfaces to maintain its commanded position relative to the lead. The relative location requiring the least thrust is then assigned as the dynamic sweet spot. The results showed that depending on the trail aircraft size, the static sweet spot might differ from the dynamic sweet spot. The effect of the leader weight and follower size on both static and dynamic sweet spot was also studied. It was discovered that the static and dynamic sweet spot location changed when the size of the trail aircraft was modified. It was also observed that the static sweet spot remained the same but the dynamic sweet spot changed when the lead aircraft weight was modified. This study, as opposed to the previous work of the authors, utilizes a different and improved aerodynamic coupling technique to model the effect of the lead on the trail aircraft.

Okolo, W., Dogan, A., and Blake, W.

"ALTERNATE TRIMMING METHODS FOR TRAILING AIRCRAFT IN FORMATION FLIGHT"

Journal of Guidance, Control, and Dynamics, Vol. 38, No. 10, October 2015, pp. 2018-2024.

This Note presented the results of using alternative trim mechanism at the static optimal location for an EQ-II aircraft trailing a KC-135R. The drag-inducing control effector deflections required to trim the induced moments on the EQ-II at the static optimal location nullified the expected benefit of formation flight. Thus, internal fuel transfer and differential thrusting were employed to reduce the deflections of the aileron and rudder, respectively. Combined, these techniques yielded fuel savings of 7 percent for the EQ-II behind the KC-135R. The fuel saving was increased to 8 percent when the alternative trimming methods were used for the EQ-II behind a heavy KC-135R. Although this fuel configuration

was the best-case scenario for the benefit of fuel transfer because it enables the largest lateral c.m. shift by fuel transfer, it was impossible to significantly affect the elevator deflections using internal fuel transfer.

Okonkwo, P. and Smith, H.

"REVIEW OF EVOLVING TRENDS IN BLENDED WING BODY AIRCRAFT DESIGN"

Progress in Aerospace Sciences, Vol. 82, 2016, pp. 1-23.

The desire to produce environmentally friendly aircraft that is aerodynamically efficient and capable of conveying large number of passengers over long ranges at reduced direct operating cost led aircraft designers to develop the Blended Wing Body (BWB) aircraft concept. The BWB aircraft represents a paradigm shift in the design of aircraft. The design provides aerodynamics and environmental benefits and is suitable for the integration of advanced systems and concepts like laminar flow technology, jet flaps and distributed propulsion. However, despite these benefits, the BWB is yet to be developed for commercial air transport due to several challenges. This paper reviews emerging trends in BWB aircraft design highlighting design challenges that have hindered the development of a BWB passenger transport aircraft. The study finds that in order to harness the advantages and reduce the deficiencies of a tightly coupled configuration like the BWB, a multidisciplinary design optimization should be conducted with good handling and ride quality as objective functions within acceptable direct operating cost and noise bounds.

Okulov, V. L.

"ON THE STABILITY OF MULTIPLE HELICAL VORTICES"

J. Fluid Mech., Vol. 521, 2004, pp. 319-342

The classical problem of linear stability of a regular N-gon of point vortices to infinitesimal space displacements from an equilibrium of the vortex configuration is generalized to the one for N helical vortices (couple, triplet, etc., $N > 1$) for the first time. Because of this consideration, the analytical form for the stability boundaries has been obtained. This solution allows an efficient analysis to be made of the existence of stable helical vortex arrays, which were repeatedly observed in practice. Such a stability problem was earlier considered in theory, but only for the case of a plane polygonal array of N point vortices. As for helical vortices, owing to their complexity, intensive study has been mainly on the self-induced motion of the vortex. The algebraic representation for the velocity of motion of the N helical vortex array was originally obtained as an additional intermediate result. The new formula allows accurate calculations to be made within the whole range of helical pitch variations and has a simpler form than the known asymptotic expressions. Solution of these two classical problems of vortex dynamics has significance both for theoretic and applied mechanics, as well as for many other areas of natural science, where the rotor (vortex) concept is the basic one.

Okulov, V. L. and Sorensen, J. N.

"INSTABILITY OF A VORTEX WAKE BEHIND WIND TURBINES"

Doklady Physics, Vol. 49, No. 12, 2004, pp. 772-777

Modern wind-power generators (wind turbines) often are grouped together to ensure an increased operating efficiency at the expense of using many turbines in the same terrain area. However, in this case, one or several turbines can turn out to be in the wake beyond other turbines. The airflow beyond a wind turbine is represented by a system of intense rotational helical vortices determining the dynamics of a far wake. The wake produces a significant periodic load for the structure of a wind turbine present in the wake. This fact, naturally, results in a reduction of the turbine in-service time. However, as is well known, for certain operating regimes of wind turbines, the vortex wake becomes unstable and breaks down. If a turbine is in a stable vortex wake, then the interaction with it may have more significant consequences than in the case of wake breakdown. Therefore, analysis of stability conditions for a vortex system simulating the vortex wake beyond wind turbines, screws, and aerodynamic propellers is of great practical importance.

Okulov, V. L., Sorensen, J. N. and Wood, D. H.

"THE ROTOR THEORIES BY PROFESSOR JOUKOWSKY: VORTEX THEORIES"

Progress in Aerospace Sciences, Vol. 73, 2015, pp. 19-46.

This is the second of two articles with the main, and largely self-explanatory, title 'Rotor theories by Professor Joukowski.' This article considers rotors with finite number of blades and is subtitled 'Vortex theories.' The first article with subtitle 'Momentum theories' assessed the starring role of Joukowski in aerodynamics in the historical context of rotor theory. The main focus in both articles is on wind turbine rotors, but much of the basic theory applies to propellers and helicopters as well. Thus, this second article concentrates on the so-called blade element theory, the Kutta-Joukowski theorem, and the development of the rotor vortex theory of Joukowski. This article is largely based on our own work, which constitutes the first successful completion and further development of Joukowski's work by deriving the first analytical solution of his rotor. This rotor has a finite number of blades and will be compared with the rotor analysis of Betz and of others of the German school of aerodynamics.

Okuno, Y. and Matayoshi, N.

"EFFECTS OF LARGE AIRPLANES' WAKE TURBULENCE ON SMALL AIRCRAFT"

Report JAXA-RR-07-029, 2008, Flight Systems Research Center, Tokyo, Japan.

Flight simulation test results are presented, comparing the effects on a small airplane Dornier Do228 and a helicopter Mitsubishi MH2000 encountering B747-400's wake turbulence. Results show that the response of the helicopter is much smaller than that of the airplane. The effects of some parameters such as visibility are examined. Information display system is also developed which shows the pilot the location and strength of the wake turbulence measured by a ground-based Doppler-lidar system.

Olcay, A. B. and Krueger, P. S.

"MEASUREMENT OF AMBIENT FLUID ENTRAINMENT DURING LAMINAR VORTEX RING FORMATION"

Experiments in Fluids, Vol. 44, 2008, pp. 235-247

Planar laser induced fluorescence (PLIF) and digital particle image velocimetry (DPIV) combined with Lagrangian coherent structure (LCS) techniques are utilized to measure ambient fluid entrainment during laminar vortex ring formation and relate it to the total entrained volume after formation is complete. Vortex rings are generated mechanically with a piston-cylinder mechanism for a jet Reynolds number of 1,000, stroke ratios of 0.5, 1.0 and 2.0, and three velocity programs (Trapezoidal, triangular negative and positive sloping velocity programs). The quantitative observations of PLIF agree with both the total ring volume and entrainment rate measurements obtained from the DPIV/LCS hybrid method for the jet Reynolds number of 1,000, trapezoidal velocity program and stroke ratio of 2.0 case. In addition to increased entrainment at smaller stroke ratios observed by others, the PLIF results also show that a velocity program utilizing rapid jet initiation and termination enhances ambient fluid entrainment. The observed trends in entrainment rate and final entrained fluid fraction are explained in terms of the vortex roll-up process during vortex ring formation.

Olendraru, C. and Sellier, A.

"VISCOUS EFFECTS IN THE ABSOLUTE-CONVECTIVE INSTABILITY OF THE BATCHELOR VORTEX"

J. Fluid Mech., Vol. 459, 2002, pp. 371-396

The effects of viscosity on the instability properties of the Batchelor vortex are investigated. The characteristics of spatially amplified branches are first documented in the convectively unstable regime for different values of the swirl parameter q and the co-flow parameter a at several Reynolds numbers Re . The absolute-convective instability transition curves, determined by the Briggs-Bers zero-group velocity criterion, are delineated in the (a, q) -parameter plane as a function of Re . The azimuthal wavenumber m of the critical transitional mode is found to depend on the magnitude of the swirl q and on the jet ($a > -0.5$) or wake ($a < -0.5$) nature of the axial flow.

Olsen, J. H.

"AIRCRAFT WAKE TURBULENCE - AN EXPANDING AREA OF LOW-SPEED AERODYNAMICS RESEARCH"

Proceeding of the National Aerospace Electronics Conf., IEEE, 1971, pp. 17-22

A review of recent findings on the structure of a vortex wake and its interactions with following aircraft is given. Formation and disintegration processes are discussed including recently discovered instability mechanisms. Interactions between a wake and a following aircraft are shown to depend primarily on the circulation of the wake and the span of the following aircraft. Various methods suggested for reducing wake hazards are discussed. Finally, areas for further research are suggested.

Olsen, J. H.

"CONFIGURATION EFFECTS ON WAKE STRUCTURE AND AIRCRAFT INTERACTION"

FAA Symposium on Turbulence, Federal Aviation Administration, Washington, DC, March 1971, p. 24

A survey of results of recent flight tests and laboratory experiments was presented with discussion of possible means for reducing the hazard of a wake. Wing modifications, engine placement, and instability mechanisms were discussed as means for increasing the vortex core diameter. The possibility of shortening the hazardous region of the wake by exciting a natural instability of the vortex pair was described.

Olsen, J. H.

"RESULTS OF TRAILING VORTEX STUDIES IN A TOWING TANK"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 455-472

Flow visualization studies were performed in a towing tank using an electrochemically activated dye. Although test Reynolds numbers were far below flight Reynolds numbers, the results were strikingly like flight test data. Two types of instability were observed in the tank. An instability associated with the axial flow within the core was observed to destroy the flow near the core without destroying the motion far from the core. A second instability involving the mutual interaction of the two vortices was observed but somewhat masked by the first instability.

Olsen, J. H.

"RESULTS OF TRAILING VORTEX STUDIES IN A TOWING TANK"

D1-82-1004, September 1970, Boeing Research Labs, Seattle, WA

Flow visualization studies were performed in a towing tank using an electrochemically activated dye. Although test Reynolds numbers were far below flight Reynolds numbers (10 to the 4th versus 10 to the 7th power), the results were strikingly like flight test data. Two types of instability were observed in the tank. An instability associated with the axial flow within the core was observed to destroy the flow in the neighborhood of the core without destroying the motion far from the core. A second instability involving the mutual interaction of the two vortices was observed but somewhat masked by the first instability.

Olsen, J. H., Goldberg, A. and Rogers, M., editors

"AIRCRAFT WAKE TURBULENCE AND ITS DETECTION"

1st ed., Plenum Press, New York, 1971

Proceedings of a Symposium on Aircraft Wake Turbulence held in Seattle, Washington, September 1-3, 1970. The volume covers the properties of wakes, including their formation, stability, and decay, and provides data on interactions between wakes and following aircraft as well as experimental methods of observing wake properties.

Olsen, M. E.

"LagRST MODEL PREDICTIONS OF A WINGTIP VORTEX FLOWFIELD"

AIAA Paper 2015-2923, June 2015, Dallas, TX.

The performance of the new LagRST models is compared with curvature corrected eddy viscosity RANS models on the Chow-Zilliac wingtip flowfield. The Reynolds-stress models provide very good predictions of this flow without any additional curvature corrections. Along with comparison of predictions of the vortex itself, some of the other measurements included in the flowfield are compared with the predictions in the wake and over the wing. Differences in predictions between the various RANS models in the wake region are small -- not substantial, and all predictions are in line with experimental measurements from 0.005c to 0.67c downstream of the trailing edge, at odds with what self-similar wake analysis would predict.

Olsthoorn, J. and Dalziel, S. B.

"THREE-DIMENSIONAL VISUALIZATION OF THE INTERACTION OF A VORTEX RING WITH A STRATIFIED INTERFACE"

Journal of Fluid Mechanics, Vol. 820, 2017, pp. 549-579.

The study of vortex-ring-induced stratified mixing has long played a key role in understanding externally forced stratified turbulent mixing. While several studies have investigated the dynamical evolution of such a system, this study presents an experimental investigation of the mechanical evolution of these vortex rings, including the stratification-modified three-dimensional instability. The aim of this paper is to understand how vortex rings induce mixing of the density field. We begin with a discussion of the Reynolds and Richardson number dependence of the vortex-ring interaction using two-dimensional particle image velocimetry measurements. Then, using modern imaging techniques, we reconstruct from an experiment the full three-dimensional time-resolved velocity field of a vortex ring interacting with a stratified interface. This work agrees with many of the previous two-dimensional experimental studies, while providing insight into the three-dimensional instabilities of the system. Observations indicate that the three-dimensional instability has a similar wavenumber to that found for the unstratified vortex-ring instability at later times. We determine that the time scale associated with this instability growth has an inverse Richardson number dependence. Thus, the time scale associated with the instability is different from the time scale of interface recovery, possibly explaining the significant drop in mixing efficiency at low Richardson numbers. The structure of the underlying instability is a simple displacement mode of the vorticity field.

Olwi, I. and Ghazi, M.

"EFFECT OF WING TIP VORTICES ON A TRAILING AIRCRAFT"

AIAA Journal, Vol. 30, No. 9, September 1992, pp. 2186-2187

The effect of trailing vortices from a large leading wing on a trailing aircraft is studied experimentally. The aerodynamic response of the trailing aircraft is examined through measurements of lift, drag, and pitching moment for various angles of attack of the two models and different separation distances between them. The results show that trailing vortices cause a remarkable loss of lift on the trailing aircraft. This phenomenon becomes more significant as the angle of attack of the leading object is increased. Results demonstrate that in order to maintain the same lift, drag would increase as the leading wing angle of attack is increased.

Ooga, Y.

"WAKE TURBULENCE DETECTING SYSTEM"

US Patent 6,424,408 B1, July 2002.

Reducing blind spots of a laser radar observing wake turbulence is required for detecting efficiently the wake turbulence which appears behind the main wings of an aircraft and affects the flight of other aircraft. A first laser radar and a second laser radar each emit a laser beam from different positions. A signal processing device produces wake turbulence information based on the reception signal of the first and second laser radar. Further, the signal processing device specifies wake turbulence information for producing display data either by making a composite of wake turbulence information of two laser radar whose observation areas do not overlap each other or by selecting the larger value of wake turbulence information from two laser radar whose observation areas overlap each other and produces display data for indicating wake turbulence information on monitor display based on the specified wake turbulence information.

Oon, E. H.

"DECAY OF TRAILING VORTICES"

ARC-CP-1238, June 1971, Bristol Univ., Bristol, England. (Also, ARC-33215.)

Model wings of various planforms were plunged vertically into a water tank and the vortex patterns on the surface were studied. For each wing the wake drift rate was found to increase with incidence and to decrease with increasing core separation. The wake started off with discrete vortex cores which grew independently, maintained their initial separation, and had peak velocities which decayed as time to the minus one-half power. The edges of the cores ultimately came very close together and thereafter separation distance between the core centers increased with time, and the peak velocities tended to decay as the reciprocal of time.

Opoku, D. G. and Nitzsche, F.

"ACOUSTIC VALIDATION OF A NEW CODE USING PARTICLE WAKE AERODYNAMICS AND GEOMETRICALLY-EXACT BEAM STRUCTURAL DYNAMICS"

Proceedings 29th European Rotorcraft Forum, September 2003, Friedrichshafen, Germany.

This paper describes the validation of a new code for predicting both aeroacoustic and aeroelastic behavior of hingeless rotors. The structural component was based on a non-linear beam element model considering small strains and finite rotations, which uses a mixed variational intrinsic formulation. The aerodynamic component was built on a low-order panel method incorporating a vortex particle free-wake model. The aerodynamic and structural components were combined to form a closely coupled aeroelastic code that solves in the time-domain. The loading and thickness noise terms for the aeroacoustic calculations were calculated from the aerodynamic data using a formulation based on the Ffowcs Williams-Hawkings equation. The code was successfully validated for acoustic signature and BVI predictions using test cases from the HELINOISE program.

Opoku, D. G., Triantos, D. G., Nitzsche, F. and Voutsinas, S. G.

"ROTORCRAFT AERODYNAMIC AND AEROACOUSTIC MODELLING USING VORTEX PARTICLE METHODS"

ICAS Paper 2002-299, September 2002, Toronto, Canada.

The initial development of a combined active aeroelastic aeroacoustic rotorcraft code is discussed. The GENeral Unsteady Vortex Particle code (GENUVP) is used as the aerodynamic component of the combined code. A brief discussion of the theory behind GENUVP's use of an unsteady panel method with a vortex particle wake is presented. Modifications to GENUVP to increase its computational efficiency are discussed. The implementation of a new aeroacoustic component in GENUVP is summarized. An overview of the combined active aeroelastic aeroacoustic code under development is presented. Results from the current work, including aerodynamic modelling of the NASA/ARMY/MIT Active Twist Rotor (ATR) and acoustic modelling of a NASA scale UH1H rotor are presented.

Orangi, S., Foster, M. R. and Bodonyi, R. J.

"ON THE STRUCTURE OF A THREE-DIMENSIONAL COMPRESSIBLE VORTEX"

Computers and Fluids, Vol. 30, Issue 1, September 2000, pp. 115-135.

We present here self-similar solutions of the equations of motion of a viscous, heat conducting gas, for a family of slender vortices. Slenderness makes possible use of the boundary-layer-like 'quasi-cylindrical approximation.' For our solutions, velocity components at the vortex edge behave like a power of the axial coordinate, and the vortex core width varies like a power of the same variable -- $1/2$ in many of the results presented here. Effects due to the temperature dependence of the viscosity, and

varying the Prandtl number and specific-heat ratio are included. It appears that the location of the vortex 'edge' is actually an independently specifiable parameter of the solution.

O'Regan, M. S., Griffin, P. C. and Young, T. M.

"NUMERICAL AND EXPERIMENTAL INVESTIGATION OF THE MEAN AND TURBULENT CHARACTERISTICS OF A WING-TIP VORTEX IN THE NEAR FIELD"

Proceedings of Institution of Mechanical Engineers; Part G: Journal of Aerospace Engineering, Vol. 228, No. 13, 2014, pp. 2516-2529.

The near-field (up to three chord lengths) development of a wing-tip vortex is investigated both numerically and experimentally. The research was conducted in a medium speed wind tunnel on a NACA 0012 square tip half-wing at a Reynolds number of 320,000. A full Reynolds stress turbulence model with a hybrid unstructured grid was used to compute the wing-tip vortex in the near field while an x-wire anemometer and five-hole probe recorded the experimental results. The mean flow of the computed vortex was in good agreement with experiment as the circulation parameter was within 6 percent of the experimental value at $x/c=0$ and angle of attack of 10 degrees and the crossflow velocity magnitude was within 1 percent of the experimental value at $x/c=1$ and angle of attack of 5 degrees. The trajectory of the computed vortex was also in good agreement as it had moved inboard by the same amount (10 percent chord) as the experimental vortex at the last measurement location. The axial velocity excess is under predicted for angle of attack of 10 degrees, whereas the velocity deficit is in relatively good agreement for angle of attack of 5 degrees. The computed Reynolds shear stress component is in good agreement with experiment at $x/c=0$ for angle of attack of 5 degrees, but is greatly under predicted further downstream and at all locations for angle of attack of 10 degrees. It is thought that a lack of local grid refinement in the vortex core and deficiencies in the Reynolds stress turbulence model may have led to errors in the mean flow and turbulence results respectively.

O'Regan, M. S., Griffin, P.C., McNicholas, G. and Young, T. M.

"EXPERIMENTAL/NUMERICAL INVESTIGATION OF A WINGTIP VORTEX IN THE NEAR-FIELD"

AIAA Paper No. 2012-3331, June 2012, New Orleans, LA.

The three-dimensional wake in the near-field (x/c from 0 to 3) of a wingtip vortex has been studied both experimentally and computationally. The research was conducted in the University of Limerick's medium speed wind tunnel on a NACA 0012 square tip half wing at a Reynolds number of 310,000. Single hot wire measurements recorded a maximum turbulence intensity of 9 percent just after the trailing edge. Maximum turbulence intensity after $x/c = 0$ is observed in the vortex core which decays with downstream distance. Five-hole probe mean velocity measurements revealed jet like and wake like axial velocity profiles depending on wing angle of attack, with values of $1.33U$ and $0.83U$ (U is the freestream velocity) being measured for 10 degrees and 5 degrees. Axial vorticity is also observed to increase gradually with downstream distance. A full Reynolds stress turbulence model with a second order upwind differencing scheme is used to compute the vortex in the near-field. Vortex structure and

trajectory correlate well with experiment. It is thought that the dissipative nature of the second order convection scheme led to discrepancies between numerical and experimental results.

Orlandi, P.

"VORTEX DIPOLE REBOUND FROM A WALL"

Phys. Fluids A, Vol. 2, No. 8, August 1990, pp. 1429-1436

Accurate numerical simulations of vortex dipoles impinging on flat boundaries have revealed interesting new features. In the case of free-slip boundaries the dipole does not rebound from the wall. In the case of nonslip walls rebounding occurs and complex interactions of secondary and tertiary vortices appear. The numerical simulation of the first dipole rebound from the wall agrees with experimental visualizations. Numerical experiments extending in time beyond the real experiments show multiple rebounding. Each rebound is associated with the detachment of a secondary vorticity layer from the wall; these layers merge, and at a value of Reynolds number $Re = 1600$, form a new dipole. This dipole has sufficient circulation to induce on itself a motion in the opposite direction to the motion of the initial dipole.

Orlandi, P.

"TWO-DIMENSIONAL AND THREE-DIMENSIONAL DIRECT NUMERICAL SIMULATION OF CO-ROTATING VORTICES"

Physics of Fluids, Vol. 19, 2007, pp. 013101-1 -- 013101-18

Two-dimensional (2D) and three-dimensional (3D) simulations are presented for co-rotating vortices with distributed vorticity at different values of the separation distance b . The ratio between the vortices' radius a and b is smaller than the critical value $a/b \sim 0.30$ for merging in inviscid conditions of blobs of constant vorticity. The dependence of merging on Reynolds number and on a/b has been investigated in 2D simulations. In 2D the resolution can be increased to perform simulations at $Re = 30000$ when very long filaments are generated.

Orlandi, P. and Verzicco, R.

"VORTEX RINGS IMPINGING ON WALLS: AXISYMMETRIC AND THREE-DIMENSIONAL SIMULATIONS"

Journal of Fluid Mechanics, Vol. 256, 1993, pp. 615-646.

Accurate numerical simulations of vortex rings impinging on flat boundaries revealed the same features observed in experiments. The results for the impact with a free-slip wall compared very well with previous numerical simulations that used spectral methods, and were also in qualitative agreement with experiments. The present simulation is mainly devoted to studying the more realistic case of rings interacting with a no-slip wall, experimentally studied by Walker et al. (1987). All the Reynolds numbers studied showed a very good agreement between experiments and simulations, and,

at $Re > 1000$ the ejection of a new ring from the wall was seen. Axisymmetric simulations demonstrated that vortex pairing is the physical mechanism producing the ejection of the new ring. Three-dimensional simulations were also performed to investigate the effects of azimuthal instabilities. These simulations have confirmed that high-wavenumber instabilities originate in the compression phase of the secondary ring within the primary one. The large instability of the secondary ring has been explained by analysis of the rate-of-strain tensor and vorticity alignment. The differences between passive scalars and the vorticity field have been also investigated.

Orlandi, P., Carnevale, G. F. and Shariff, K.

"THERMAL PERTURBATION OF TRAILING VORTICES"

European Journal of Mechanics, B - Fluids, Vol. 20, 2001, pp. 511-524

The possibility of diminishing the danger of trailing vortices through thermal forcing is investigated. It is shown that heating the vortices would have two beneficial effects. First, it would cause the vortices to descend more rapidly thus clearing the flight path more quickly. Second, it would cause the vortices to draw closer together, thus greatly increasing the growth rate of the short-wave instabilities that can ultimately destroy the vortices through cross-diffusion.

Orlandi, P., Carnevale, G. F., Lele, S. K. and Shariff, K.

"DNS STUDY OF STABILITY OF TRAILING VORTICES"

Proceedings of the Summer Program, 1998, Center for Turbulence Research, pp. 187-208

Three-dimensional numerical simulations are used to investigate the possibility of diminishing the strength of trailing vortices. Direct numerical simulation is first used to reproduce results of recent laboratory experiments on the short-wave co-operative instability for two counter-rotating vortices. The effect of perturbing the vortices by internal and external density perturbations is considered. It is found that perturbing trailing vortices with temperature variations may be a useful means of initiating the short-wave instability and ultimately causing the cross diffusion of vorticity necessary to destroy the coherence and strength of the trailing vortices.

Orlandi, P., Eggermann, P. and Hopfinger, E. J.

"VORTEX RINGS DESCENDING IN A STRATIFIED FLUID"

Physics of Fluids, Vol. 10, No. 11, November 1998, pp. 2819-2827

Experimental and numerical results are presented of a laminar vortex ring descending in a linearly stratified fluid. It is observed that the ring shrinks in size as it penetrates the stratified environment and has nearly disappeared when it comes to a stop. This behavior is similar to what was observed by

Maxworthy for a turbulent vortex ring in a stratified environment. The ring position and size collapse on a single curve when appropriately scaled. It is shown that baroclinic vorticity production of opposite sign and cross diffusion is the cause for the disappearance of the ring. The instantaneous ring Froude number is always greater than or equal to 1 and, therefore, no internal waves are generated.

Orloff, K. L.

"TRAILING VORTEX WIND-TUNNEL DIAGNOSTICS WITH A LASER VELOCIMETER"

J. Aircraft, Vol. 11, No. 8, August 1974, pp. 477-482

A two-dimensional laser velocimeter whose focal volume can be rapidly traversed through a flow-field has been used to overcome the problem introduced by excursions of the central vortex filament within a wind-tunnel test section. The operation of the instrument is reviewed and data are presented which accurately define the trailing vortex from a square-tipped rectangular wing. Measured axial and tangential velocity distributions are given, both with and without a vortex dissipator panel installed. From the experimental data, circulation and vorticity distributions are obtained and the effect of turbulence injection into the vortex structure is discussed.

Orloff, K. L.

"SPANWISE LIFT DISTRIBUTION ON A WING FROM FLOWFIELD VELOCITY SURVEYS"

J. Aircraft, Vol. 17, No. 12, December 1980, pp. 875-882

The application of the incompressible three-dimensional momentum integral equation to a finite wing is reviewed. The objective is to interpret the resulting equations in a way that suggests an alternate experimental method for determining the spanwise distribution of lift. Consideration is given to constraints that must be placed on the character of the vortex wake of the wing to provide the familiar relationship between lift and bound vorticity. A novel technique is then presented for obtaining, from behind the wing, the spanwise lift distribution from velocity surveys that are made over only a short distance above and below the wing trailing edge. The necessary formalism is developed to use these measured values to obtain the actual span loading by using an equivalent single-horseshoe vortex model to account for the unmeasured portion of the downward (or upward) momentum. The results of a numerical simulation are presented for a typical loading distribution. The technique is then verified experimentally using laser velocimeter data for the flowfield around a model wing.

Orloff, K. L. and Ciffone, D. L.

"VORTEX MEASUREMENTS BEHIND A SWEEPED WING TRANSPORT MODEL"

J. Aircraft, Vol. 11, No. 6, June 1974, pp. 362-364

A backscattering laser Doppler velocimeter (LDV) which simultaneously senses two components of the velocity (axial and tangential), has been used to traverse and measure the velocity distribution in

the near wake of a swept wing semispan transport model in the NASA-Ames 7x10-foot wind tunnel. These measurements demonstrate the effect of flap deflection (flap-retracted and flaps deployed 27 deg.) on the velocity profile.

Orloff, K. L. and Grant, G. R.

"THE APPLICATION OF A SCANNING LASER DOPPLER VELOCIMETER TO TRAILING VORTEX DEFINITION AND ALLEVIATION"

AIAA Paper No. 1973-0680, Palm Springs, CA, 1973

A two-dimensional laser Doppler velocimeter whose focal volume can be rapidly traversed through a flow field has been used to overcome the problem introduced by excursions of the central vortex filament within a wind-tunnel test section. The operation of the instrument is reviewed and data are presented which accurately define the trailing vortex from a square-tipped rectangular wing. Measured axial and tangential velocity distributions are given, both with and without a vortex dissipator panel installed. From the experimental data, circulation and vorticity distributions are obtained and the effect of turbulence injection into the vortex structure is discussed. The experimental velocity profiles are compared to the inviscid Betz theory (as presented by Rossow) and to the functional forms for the logarithmic and defect regions (given by Nielsen and Schwind).

Orloff, K. L., Ciffone, D. L. and Lorincz, D.

"AIRFOIL WAKE VORTEX CHARACTERISTICS IN THE FAR FIELD"

NASA TM-X-62318, November 1973, NASA Ames Research Center, Moffett Field, CA

Tangential and axial velocity profiles were measured in the far field wake vortices of several different airfoils. The results are summarized and discussed. A scanning laser velocimeter was used to obtain data up to 1000 chord lengths behind airfoils with rectangular, diamond-shaped, and swept wing planforms at several different angles of attack. The results show general agreement with wind tunnel measurements made in the near field. The results identify two separate flow regions for the dependence of vortex maximum tangential velocity on downstream distance: an inviscid region where the velocity remains constant after rollup to downstream distances of 200 chord lengths, and then a decay or viscous region that persisted to the limit of the test distance. The decay rates appear to be sensitive to both angle of attack and span loading. The maximum tangential velocity for downstream distances to 40 span lengths was reduced by a factor of 2 by changing from an elliptic (swept wing) or rectangular span loading to a triangular-like span loading (diamond-shaped planform wing). Measured axial velocity defects are shown to agree with those predicted by laminar theory.

Orman, J. C. and Hockaday, S. L. M.

"CAPACITY PAYOFFS AT LARGE HUB AIRPORTS FROM ATC INITIATIVES"

Proceedings Annual Assembly Meeting, RTCA, Washington, DC, November 1979, pp. 21-38

The paper reviews the current status of system capacity and delay analysis with particular reference to ongoing FAA efforts in the E&D field. The main emphasis of the capacity element of existing E&D programs is on increasing system capacity through reductions in minimum IFR radar longitudinal separations between arrival aircraft. The biggest problem associated with achieving reduced longitudinal separation of any type is the ability to deal effectively with wake turbulence. Analysis at high-activity airports indicates that gains in system capacity and reductions in aircraft travel time may be achieved by methods other than reduction in minimum longitudinal separations. A summary of 14 of the more promising methods is presented, including examples of potential site-specific applications and benefits.

Ormiston, R. A.

"AN ACTUATOR DISC THEORY FOR ROTOR WAKE INDUCED VELOCITIES"

AGARD CP-111, Aerodynamics of Rotary Wings, February 1972, pp. 2-1 - 2-19

A general actuator disc theory is presented for predicting the time-averaged downwash distribution, and steady state force and moment response characteristics of helicopter rotors in forward flight. Particular attention is given to a proper definition of the rotor potential flow problem. The formulation of the theory is conceptually based on classical fixed-wing lifting-line theory to enhance its versatility and provide insight about the complex physical features of the rotor downwash distribution. It is shown that the rotor wake vorticity can be assumed to lie in a flat planar wake for a wide range of flight conditions, thus simplifying the Biot-Savart integration for the downwash.

Ormsbee, A. I.

"STUDY OF THE FEASIBILITY OF USING A SAILPLANE AS AN INSTRUMENT PLATFORM FOR THE STUDY OF WAKE VORTEX PHENOMENA"

NASA CR-140603, September 1974, Illinois Univ., Urbana, IL

The feasibility of utilizing instrumentation mounted on a sailplane wing is investigated to determine vortex wakes from a large aircraft. The instrumentation consisted of static and total pressure tubes and a rotating vane vorticity meter mounted in a pod on the glider wing tip. It was concluded that the study was not feasible.

Ormsbee, A. I., Bragg, M. B., Maughmer, M. D. and Jordan, Jr., F. L.

"SCALING WAKE-PARTICLE INTERACTIONS FOR AERIAL APPLICATIONS RESEARCH"

J. Aircraft, Vol. 18, No. 7, July 1981, pp. 592-596

The differential equation for the trajectory of a spherical particle injected into an aircraft wake was developed and the proper scaling relations extracted. After some simplification, a convenient set of similarity parameters was established. Using these similarity parameters a scale-model test program was designed and performed in the NASA Langley Vortex Research Facility. The results of the tests demonstrated the validity of the similarity parameters in conducting scale-model testing for aerial applications research.

Ornberg, T.

"A NOTE ON THE FLOW AROUND DELTA WINGS"

KTH AERO TN 38, 1954, Royal Institute of Technology, Stockholm, Sweden.

To find reasons for some irregularities in delta wing force and moment curves as measured in wind-tunnels, some investigations have been made of the flow on and around wings of this type and its effect on the pressure distributions. The flow on and around wings with various sweep angles and profile thicknesses has been investigated at low speeds (the boundary layer flow on the suction side also at supersonic speeds). Low speed pressure distributions have been measured on and above the suction side of these wings. The low-speed investigations show that edge vortices are produced by separation at highly swept leading edges and have a marked effect on the surface pressure distribution. The cores of these vortices have also been localized and measured at different angles of incidence. The supersonic tests suggest that the vortices still exist provided that the leading edge is well behind the nose Mach cone. The behavior of these vortices under different conditions appears to explain the above-mentioned irregularities in force and moment curves.

Ortega, J. M.

"STABILITY CHARACTERISTICS OF COUNTER-ROTATING VORTEX PAIRS IN THE WAKES OF TRIANGULAR-FLAPPED AIRFOILS"

PhD Thesis, Spring 2001, University of California, Berkeley, CA.

A rapidly growing instability is observed to develop between unequal strength, counter-rotating vortex pairs in the wakes of airfoils with outboard triangular flaps. To investigate the physical mechanisms for this instability, a linear stability analysis is performed on a single vortex pair. This analytical model reveals that the instability is driven by the strain rate field from one vortex acting on the perturbations of its neighboring vortex. Another linear stability analysis is conducted to include the effects of the other counter-rotating vortex pair. The qualitative features of the instability, such as its wavelength and non-linear evolution, are examined by flow visualization measurements that are made in a towing tank facility at a chord Reynolds number of order 100,000. From these observations, a sinuous instability is seen to develop on the weaker flap vortices and have a wavelength of order one wingspan. The instability wavelengths that are observed in the flow visualization data compare favorably with those predicted by the two- and four-vortex linear stability analyses, demonstrating that the analytical models capture the essential physics of the instability growth. Quantitative

measurements of the vortex wakes are made with a PIV technique, allowing the vortex structure, trajectories, kinetic energy, and distribution to be assessed up to several hundred wingspans downstream of the airfoils. Additionally, the circulation-based Reynolds number is seen to be of order 100,000. The PIV data indicate that the wake's two-dimensional kinetic energy decreases substantially as the instability transforms the two-dimensional nature of the wake into a three-dimensional one. Finally, the wake alleviation properties of this instability are measured by computing the maximum rolling moment and downwash that a following wing might experience if it were placed in the wakes of these airfoils. These calculations show that by 75 wingspans, the wakes of the triangular-flapped airfoils have rolling moments and downwash that are always less than those of a conventional rectangular airfoil. This rapid reduction in the rolling moment and downwash leads to the conclusion that this instability between unequal strength, counter-rotating vortex pairs has the potential to solve the wake hazard problem.

Ortega, J. M.

"PASSIVE WAKE VORTEX CONTROL"

UCRL-ID-146320, Oct. 2001, University of California, Livermore, CA.

We address a concept called passive wake vortex control (PWVC), which has been demonstrated to rapidly break apart a trailing vortex wake and render it incoherent. PWVC functions by introducing unequal strength, counter-rotating control vortices next to the tip vortices (Figure 1b). The presence of these control vortices destabilizes the vortex wake and produces a rapidly growing wake instability.

Ortega, J. M. and Savas, O.

"RAPIDLY GROWING INSTABILITY MODE IN TRAILING MULTIPLE-VORTEX WAKES"

AIAA Journal, Vol. 39, No. 4, April 2001, pp. 750-754

This note presents the results from an experimental effort designed to trigger early onset of instability in wingtip vortices. The experiments involved placing close together vortices of unequal strengths and opposite signs, such that the interaction leads to a cooperative instability quicker than the classical Crow instability. The instability was first developed on the weaker flap vortices at approximately 20 spans downstream of the wing, having a wave length of the order of one wingspan. The rapid growth of the instability and the exchange of vorticity with the wingtip vortex may represent a strategy for controlling the vortex wake and, perhaps, reducing the wake hazard.

Ortega, J. M., Bristol, R. L. and Savas, O.

"WAKE ALLEVIATION PROPERTIES OF TRIANGULAR-FLAPPED WINGS"

AIAA Journal, Vol. 40, No. 4, 2002, pp. 709-721

The wake alleviation properties of wings with outboard, triangular flap extensions are estimated using data from particle image velocimetry. The experiments are conducted in a towing tank at chord-based Reynolds numbers of $O(100,000)$. The triangular-flapped wings generate two unequal strength, counter-rotating vortex pairs that have circulation strength ratios ranging from -0.4 to -0.7. Introducing the oppositely signed flap vortices near the tip vortices causes a rapidly growing instability to occur between the vortices on either side of the wake. The resulting nonlinear interactions between the vortices result in a wake that is highly three-dimensional and incoherent. These effects are reflected in a marked decrease in both the rolling moment and downwash on a simulated following wing. To determine the wake alleviation properties of the triangular-flapped wings, their wakes are compared to that of a conventional, rectangular wing. For all the experimental runs, the wakes of the triangular-flapped wings have maximum rolling moments and downwashes that are substantially less than those of the rectangular wing. The results indicate that the instability in the wake of the triangular-flapped wings offers a possible mechanism to reduce significantly the wake hazard problem.

Ortega, M. A., Girardi, R. M. and Silvestrini, J. H.

"THE FORMATION REGION BEHIND A BLUNT BODY FITTED WITH SPLITTER PLATES"

AIAA Paper No. 2007-132, Reno, NV, January 2007

An investigation of the formation region at the base of a two-dimensional blunt-trailing-edged body is attempted with the help of a DNS numerical tool. This work is a natural extension, focused on the theme of the flow about blunt bodies, of a former research effort by the present authors. Here, the formation region is better investigated, and the aim is directed towards the understanding of the most important physical mechanisms that operate upon this very important region. It is known that, what happens in this region is decisive to the characteristics of the following wake. In principle, the study is initially based on the idea that the extent of the formation region is given by the position, in relation to the base, at which the velocity fluctuation is larger. We, then, concentrate on the analysis of several aspects related to this position, trying to relate it in some way to the idea of the vortex's formation. For example, the dependence of the formation region extent as function of Reynolds number and splitter plate length is analyzed, and a comparison with the formation of the vortices in real time is attempted.

Ortiz, S., Donnadieu, C., Chomaz, J.-M. and Billant, P.

"RECEPTIVITY AND TRANSIENT GROWTH IN WAKES"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

We investigate numerically the transient growth of three-dimensional secondary instability of wakes forming behind a thin flat plate (von Karman vortex street) and an aircraft (vortex dipole). An aircraft wake is made of counter-rotating vortices and is known to be affected by a long (Crow) and a short (elliptic) wavelength instability. With the same numerical techniques developed on the von Karman vortex street, we recover instability peaks corresponding to Crow and elliptic modes but also observe

less unstable oscillatory instabilities with very broad peaks that seem to correspond to higher order elliptic instability. The study of the transient growth demonstrates the crucial role of the region of maximum strain that, for a vortex dipole, is not located close to the hyperbolic point but inside the cores of the vortices. Further investigations on the dynamics of trailing vortices in stratified fluids will be performed.

Oshime, Y., Izutsu, N., Oshima, K. and Hussain, A. K. M. F.

"BIFURCATION OF AN ELLIPTIC VORTEX RING"

Fluid Dynamics Research, Vol. 3, 1988, pp. 133-139.

Time-dependent vorticity fields of elliptic vortex rings of aspect ratios 2, 3 and 4 were measured by means of hot-wire anemometry. The time evolution of their vorticity fields was analyzed and the processes of vortex ring formation, advection, interaction and decay, and the mechanism of vortex bifurcation are studied. The following crosslinking model is proposed. A thick vortical region composed of many equivalent vortex filaments with distributed cores is initially formed at the orifice and they behave as inviscid filaments. The elliptic ring deforms and the end parts of its major axis get closer. Then, the vortex filaments interact at the touching point and the ring partially bifurcates. Almost simultaneously, turbulent spot appears at this point, and propagates around the ring cross section, thus preventing further bifurcation. And it becomes a turbulent blob. This model is also supported by numerical simulation by a high-order vortex method and the Navier-Stokes solution.

Osminin, R. I. and Chizhov, V. M.

"PHENOMENOLOGICAL MODEL OF FORMING FLOW ANGULARITY BEHIND AN AIRFOIL CASCADE IN THE OPEN-JET WIND TUNNEL"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 178-187

To simulate the effect of time-varying flow angularity on aircraft, tests of elastic models are carried out in wind tunnels where the variations of the incoming flow are provided with the aid of the cascades of deflectable airfoils. The amplitude of varying flow angle in the test section therewith depends on both the law of cascade angle-of-attack variation and the process of vortex generation in the shear layer at the jet boundary of the test section. Based on special studies in TsAGI's water and wind tunnels and the results of theoretical investigations into submerged jets, a phenomenological flow model has been constructed which enables reliably describing the processes of formation and development of variable flow angularity behind an airfoil cascade in open-jet wind tunnels. [In Russian.

Otheguy, P., Billant, P. and Chomaz, J.-M.

"INSTABILITY OF CO-ROTATING VERTICAL VORTICES IN A STRATIFIED FLUID"

In IUTAM Symposium on Elementary Vortices and Coherent Structures: Significance in Turbulence Dynamics, edited by S. Kida, Springer, The Netherlands, 2006, pp. 219-224.

We show numerically, theoretically, and experimentally that two co-rotating vertical vortices in a stably stratified fluid are subjected to a new three-dimensional instability similar to the zigzag instability observed on counter-rotating vortices (Billant & Chomaz, 2000). This zigzag instability induces the formation of thin horizontal layers with a thickness inversely proportional to the Brunt-Vaisala frequency. This three-dimensional instability is believed to make stratified turbulence depart from two-dimensional turbulence since it alters the merging of vortices.

Otheguy, P., Billant, P. and Chomaz, J.-M.

"THEORETICAL ANALYSIS OF THE ZIGZAG INSTABILITY OF A VERTICAL CO-ROTATING VORTEX PAIR IN A STRONGLY STRATIFIED FLUID"

J. Fluid Mech., Vol. 584, 2007, pp. 103-123

A long-wavelength stability analysis of two co-rotating Gaussian vertical vortices in an inviscid strongly stratified fluid is conducted for vortices separated by a large distance compared to their radius. This analysis predicts and explains the zigzag instability found by a numerical stability analysis in a companion paper (Otheguy, Chomaz, and Billant, J. Fluid. Mech. Vol. 553, 2006, p. 253). The zigzag instability results from the coupling between the bending perturbations of each vortex and the external strain that one vortex induces on the other. The analysis predicts that the maximum growth rate of the instability is twice the strain and that the most unstable vertical wavelength scales as the buoyancy length. The asymptotic results are in very good agreement with the numerical results.

Otheguy, P., Chomaz, J.-M. and Billant, P.

"ELLIPTIC AND ZIGZAG INSTABILITIES ON CO-ROTATING VERTICAL VORTICES IN A STRATIFIED FLUID"

J. Fluid Mech., Vol. 553, 2006, pp. 253-272

We present a three-dimensional linear stability analysis of a couple of co-rotating vertical vortices in a stratified fluid. When the fluid is non-stratified, the two vortices are unstable to the elliptic instability owing to the elliptic deformation of their core. These elliptic instability modes persist for weakly stratified flow: $F > 10$, where F is the horizontal Froude number. For strong stratification ($F < 2.85$), a new zigzag instability is found that bends each vortex symmetrically with almost no internal deformation of the basic vortices. This instability may modify the vortex merging since at every half-wavelength along the vertical, the vortices are alternately brought closer, accelerating the merging, and moved apart, delaying the merging. The most unstable vertical wavelength of this new instability is shown to be proportional to Fb where b is the distance between the vortices, implying that the vertical wavelength decreases with increasing stratification. The maximum growth rate, however, is independent of the stratification and proportional to the strain. These scaling laws and the bending motion induced by this instability are like those of the zigzag instability of a counter-rotating vortex pair in a stratified fluid.

Ott, J.

"WAKE TURBULENCE, ICING PROBED IN COMAIR BRASILIA CRASH"

Aviation Week and Space Technology, Vol. 146, No. 3, 20 January 1997, pp. 34, 3.

Safety investigators are examining an unusually large amount of data to explain why a Comair EMB-120 Brasilia, on approach to Detroit Metropolitan Airport on Jan. 9, rolled and plunged to the ground. Among investigative avenues that include icing and crew training, the NTSB is looking into the impact of the A320's wake vortex on the EMB-120. The Brasilia was approximately 3.06 mi. behind the A320 and 1,600 ft. below it during the approach.

Ould-Salihi, M. L., Cottet, G. H. and Hamraoui, M. E.

"BLENDING FINITE-DIFFERENCE AND VORTEX METHODS FOR INCOMPRESSIBLE FLOW COMPUTATIONS"

SIAM Journal of Scientific Computing, Vol. 22, No. 5, 2000, pp. 1655-1674

We describe and illustrate numerical procedures that combine grid and particle solvers for the solution of the incompressible Navier-Stokes equations. These procedures include vortex in cell (VIC) and domain decomposition schemes. Numerical comparisons with pure finite-difference methods demonstrate the effectiveness of these techniques for various flow geometries, bounded or unbounded.

Overcamp, T. J. and Fay, J. A.

"DISPERSION AND SUBSIDENCE OF THE EXHAUST OF A SUPERSONIC TRANSPORT IN THE STRATOSPHERE"

J. Aircraft, Vol. 10, No. 12, 1973, pp. 720-728

A theoretical model is presented that describes the early time history of the wake of an aircraft. This theory shows that far downstream of the aircraft, buoyancy dominates the growth of the wake. For a supersonic transport flying in the stratosphere, the stable stratification will limit the growth of the wake. Data of the visible width of the wake from laboratory experiments in a towing tank and from studies on the growth of contrails from subsonic aircraft verify the model for a neutral atmosphere. A model is developed to show that the exhaust gases of a supersonic transport can sink due to differential radiative cooling caused by the high concentration of water vapor and the lower concentration of ozone in the wake. Estimates of the rate of subsidence are given for aircraft flying between 16 and 27 km.

Overcamp, T. J. and Fay, J. A.

"DISPERSION OF SST TRAILS IN THE STRATOSPHERE"

AIAA Paper No. 1972-0650, Boston, MA, June 1972

A simple theory for the dispersion of the exhaust of a supersonic transport cruising in the stratosphere is presented. The model shows that far downstream of the aircraft, buoyancy dominates the growth of the wake. This growth is limited by the stable stratification of the atmosphere. Data on the visible width of the wake from scaled experiments in a towing tank and from studies on the growth of contrails of subsonic aircraft verify the growth of the wake in an unstratified atmosphere is predicted by the model. This growth is faster than would be predicted for the wake of an axisymmetric body with no buoyancy.

Owen, F. K. and Peake, D. J.

"VORTEX BREAKDOWN AND CONTROL EXPERIMENTS IN THE AMES-DRYDEN WATER TUNNEL"

AGARD Conf. Proceedings No. 413, Aerodynamic and Related Hydrodynamic Studies Using Water Facilities, June. 1987, pp. 2-1 to 2-10.

Flow-field measurements have been made to determine the effects of core blowing on vortex breakdown and control. The results of these proof-of-concept experiments clearly demonstrate the usefulness of water tunnels as test platforms for advanced flow-field simulation and measurement.

Owen, P. R.

"THE DECAY OF A TURBULENT TRAILING VORTEX"

ARC Report 25818, Apr. 1964, Imperial College of Science and Technology, London, England

The decay of a trailing vortex which contains turbulence in its core is examined according to the argument that the turbulence is partly sustained by and interacts with the irrotational flow through viscous diffusion of eddies across the core boundary. The region of interaction between the turbulence and the mean flow is a narrow one, separating the core from the outer irrotational flow, and expands with time as the square root of time characteristic of viscous diffusion.

Owen, P. R.

"THE DECAY OF A TURBULENT TRAILING VORTEX"

Aero. Quarterly, Vol. 21, February 1970, pp. 69-78

The decay of a trailing vortex containing a turbulent core is examined according to the argument that turbulence is partly sustained by, and interacts with, the irrotational flow through viscous diffusion of eddies across the core boundary. The region separating the core from the outer irrotational flow, in

which the interaction between the turbulence and the mean flow occurs, expands with time like $(\text{time})^{1/2}$, characteristic of viscous diffusion. The essential difference from Squire's solution found here is that the apparent viscosity is not simply proportional to the initial circulation about the vortex as he proposed, but depends on the Reynolds number defined with respect to the circulation.

Ozger, E., Schell, I. and Jacob, D.

"ON THE STRUCTURE AND ATTENUATION OF AN AIRCRAFT WAKE"

Journal of Aircraft, Vol. 38, No. 5, September-October 2001, pp. 878-887.

The results of an experimental investigation of the wake-vortex structure behind a swept and tapered wing with slats and flaps are presented. The wind tunnel test is part of a project funded by the German Research Association (DFG) to investigate the flow structure of wings with different flap extensions. The investigation aims at studying the characteristics of lift generated vortices to find ways to attenuate dangerous wake vortex encounters for following aircraft during start and landing such that an increase in airport capacity can be achieved. The wake structure is investigated for different flap settings by means of hotwire anemometry measuring the velocity field at different streamwise positions in the near field behind the wing. The measured data are evaluated to examine vortex parameters such as core radius, maximum tangential velocities, circulation distributions, turbulence levels and maximum induced rolling moments on a following aircraft. In addition, for one flap setting means of alleviation with a wing fin at different angles of incidence mounted at the outboard flap edge region are examined. The fin causes a large increase of the vortex core and a reduction of the maximum induced rolling moment within the measured region.

Ozger, E., Schell, I. and Jacob, D.

"ON THE STRUCTURE AND ATTENUATION OF AN AIRCRAFT WAKE"

AIAA Paper No. 2000-4127, August 2000, Denver, CO.

The results of an experimental investigation of the wake-vortex structure behind a swept and tapered wing with slats and flaps are presented. The wind-tunnel test is part of a project funded by the German Research Association (DFG) to investigate the flow structure of wings with different flap extensions. The investigation aims at studying the characteristics of lift generated vortices to find ways to attenuate dangerous wake vortex encounters for following aircraft during start and landing such that an increase in airport capacity can be achieved. The wake structure is investigated for different flap settings by means of hotwire anemometry measuring the velocity field at different streamwise positions in the near field behind the wing. The measured data are evaluated to examine vortex parameters such as core radius, maximum tangential velocities, circulation distributions, turbulence levels and maximum induced rolling moments on a following aircraft. In addition, for one flap setting means of alleviation with a wing fin at different angles of incidence mounted at the outboard flap edge region are examined. The fin causes a large increase of the vortex core and a reduction of the maximum induced rolling moment within the measured region.

Pachter, M., D'Azzo, J. J. and Proud, A. W.

"TIGHT FORMATION FLIGHT CONTROL"

Journal of Guidance, Control, and Dynamics, Vol. 24, No. 2, March-April 2001, pp. 246-254.

The tight formation flight control problem is addressed. The formation consists of a lead and wing aircraft, where the wing flies in tight formation with the lead, such that the lead's trailing vortices aerodynamically couple the lead and the wing, and a reduction in the formation's induced drag is achieved. A controller (i.e., a formation-hold autopilot for the wing aircraft) is designed such that the formation's geometry is maintained in the face of lead aircraft maneuvers. In the formation flight control system, the wing and lead aircraft dynamics are coupled due to kinematic effects, and, in the case of tight formations, additional aerodynamic coupling effects are introduced. These additional aerodynamic coupling effects are properly modeled. The most significant aerodynamic coupling effect introduced by tight formation flight entails the coupling of the lateral/directional channel into the altitude-hold autopilot channel. It is shown that formation-hold autopilots designed ignoring the aerodynamic coupling effect yield satisfactory performance in tight formation flight.

Padakannaya, R.

"THE VORTEX LATTICE METHOD FOR THE ROTOR-VORTEX INTERACTION PROBLEM"

NASA CR-2421, July 1974, The Pennsylvania State University, University Park, PA.

This study is concerned with the rotor blade-vortex interaction problem and the resulting impulsive air loads which generate undesirable noise levels. A numerical lifting surface method to predict unsteady aerodynamic forces induced on a finite aspect ratio rectangular wing by a straight, free vortex at an arbitrary angle in a subsonic incompressible free stream is developed first. Using a rigid wake assumption, the wake vortices are assumed to move downstream with the free stream velocity. Unsteady load distributions are obtained which compare favorably with the results of planar lifting surface theory. The vortex lattice method has been extended to a single bladed rotor operating at high advance ratios and encountering a free vortex from a fixed wing upstream of the rotor. The predicted unsteady load distributions on the model rotor blade are generally in agreement with the experimental results. This method has also been extended to full scale rotor flight cases in which vortex induced loads near the tip of a rotor blade were indicated. In both the model and the full-scale rotor blade air load circulations a flat planar wake was assumed which is a good approximation at large advance ratios because the downwash is small in comparison to the free stream at large advance ratios. The large fluctuations in the measured air loads near the tip of the rotor blade on the advance side is predicted closely by the vortex lattice method.

Padakannaya, R.

"EFFECT OF WING TIP CONFIGURATION ON THE STRENGTH AND POSITION OF A ROLLED-UP VORTEX"

M.S. Thesis, March 1970, Penn. State Univ., University Park, PA. (Also, NASA CR-66916.)

This thesis studies the effects of different wing tip configurations on the associated rolled-up vortex. The spanwise load distribution on plain rectangular wings and on wings with dropped tips was calculated by vortex lattice theory, to determine the effects of the droop on the strength and the location of the vortex. The load distribution on wings with drooped tips shows that the stronger vortex moves from the tip of the wing to the hinge of the drooped tip as the droop angle increases. The experimental results confirmed the movement of the stronger vortex from the tip of the wing to the hinge of the drooped tip as the droop angle increases.

Padfield, G. D.

"HELICOPTER ENCOUNTERS WITH AIRCRAFT VORTEX WAKES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Results are presented from a study concerning the risks associated with locating a helicopter Final Approach and Take-Off area (FATO) alongside an active runway at a busy international airport. Specifically, the problem of a helicopter encountering the shed wing tip vortex from a large transport aircraft is addressed. Data derived from measurements of tip vortices taken using a coherent laser radar located under the final approach path are used to validate a model of the distribution of the flow velocities occurring in the shed vortices. The data has also provided an opportunity to examine the length of time these vortices can retain an appreciable strength. A 'worst case' scenario is defined in which the shed wing tip vortices from a Boeing 747 are encountered by a hovering 5000 kg helicopter located at 250 m from the line of the main runway. No significant decay in vortex strength is assumed in the time taken for the vortex to travel from source aircraft to the helicopter. The simulations show, for a range of flight conditions, that the helicopter can experience transient attitude changes of up to 40 degrees and accumulated descent rates of 1500 ft/min during the encounter, assuming no pilot intervention. Established handling qualities metrics relating to attitude quickness (related to time to change attitude) and transient response following system failures have been applied to the problem and suggest that these responses may produce handling difficulties. The worst transient attitude response occurs when the helicopter encounters the inner core of the vortex. The sensitivity of the response to offsets between helicopter and vortex center during near misses is shown to be high, resulting in a decrease in the probability of the worst case occurring. In the study, the simulations were expanded to consider the influence of various helicopter design parameters on the magnitude of response and the effects of considering shed vortices from source aircraft other than the Boeing 747.

Padfield, G. D. and Turner, G. P.

"HELICOPTER ENCOUNTERS WITH AIRCRAFT VORTEX WAKES"

Twentyfifth European Rotorcraft Forum, Paper H2, September 1999, Rome, Italy, pp. H2-1 to H2-14.

This paper presents the results of a study into wake vortex-related safety issues associated with simultaneous rotary and fixed-wing aircraft operations at busy airports. An analysis conducted using both simple conceptual models and high fidelity FLIGHTLAB simulations has considered a helicopter located in the hover above the landing point and during approach and landing. Tip vortices from a Boeing 747 are shed and are assumed to be travelling in a horizontal plane by the time they reach the helicopter. A worst-case scenario is simulated, with no vortex ageing or attenuation due to ground effect. Both simple and high-fidelity simulations indicate that the rates of climb and descent induced by the vortex tails can be significant. When the helicopter flies through the vortex core, large transient excursions in attitude occur within a few seconds. When the helicopter does not pass through or close to the core, while the flight path perturbations are still significant, the attitude response is shown to be significantly reduced. The predicted cyclic control power required to counteract the vortex-induced hub moments is about 40 percent of full control, compared with more than 100 percent for an 'equivalent' fixed-wing aircraft. The control power required in the vertical, collective, axis to overcome the downdraught and updraught in the vortex tails can be as high as 15-20 percent. While the authors have not tried to make judgements as to whether pilots would find the transients manageable, an approach to quantifying the extent of the hazard has been suggested using the transients failure criteria from the handling qualities performance standard ADS-33. Combined with analysis of the likelihood of such occurrences at airports, such response criteria offer a rational approach to developing safety cases for simultaneous operations.

Padfield, G. D. and Turner, G. P.

"HELICOPTER ENCOUNTERS WITH AIRCRAFT VORTEX WAKES"

Aeronautical Journal, January 2001, pp. 1-8

This paper presents the results of a study into wake vortex-related safety issues associated with simultaneous rotary and fixed-wing aircraft operations at busy airports. An analysis conducted using both simple analytic models and high fidelity FLIGHTLAB simulations has considered a helicopter located in the hover above the landing point and during approach and landing. Tip vortices from a Boeing 747 are shed and are assumed to be travelling in a horizontal plane by the time they reach the helicopter. A worst-case scenario is simulated, with no vortex ageing or attenuation due to ground effect. Both simple and high-fidelity simulations indicate that the rates of climb and descent induced by the vortex tails can be significant. When the helicopter flies through the vortex core, moderately large transient excursions in attitude occur within a few seconds. When the helicopter does not pass through or close to the core, while the flight path perturbations are still significant, the attitude response is shown to be significantly reduced. The predicted cyclic control power required to counteract the vortex-induced hub moments is about 40% of full control, compared with more than 100% for an 'equivalent' fixed-wing aircraft. The control power required in the vertical, collective, axis to overcome the downdraught and updraught in the vortex tails can be as high as 15-20%. While the authors have not tried to make judgements as to whether pilots would find the transients manageable,

an approach to quantifying the extent of the hazard has been suggested using the transients failure criteria from the handling qualities performance standard ADS-33. Combined with analysis of the likelihood of such occurrences at airports, such response criteria offer a rational approach to developing safety cases for simultaneous operations.

Padfield, G. D., Manimala, B. and Turner, G. P.

"A SEVERITY ANALYSIS FOR ROTORCRAFT ENCOUNTERS WITH VORTEX WAKES"

28th European Rotorcraft Forum, Bristol, UK, September 2002

Our paper concerns the severity of the response of a rotorcraft encountering the vortex of a fixed-wing aircraft. One of the key questions is whether a rotorcraft designed to meet handling performance standards will have sufficient control margin for the pilot to overcome the effects of a vortex encounter. This question is addressed through an analytical study supported by preliminary piloted simulation tests. The handling criteria are found to be well suited to establishing the severity and associated hazard category of typical encounters. Cases are illustrated where insufficient control margin is available to overcome the effects of the encounter. The pilot intervention time is critical as expected. In risk assessment parlance, an intervention time of 3 seconds leads to hazardous encounters (> Level 3 HQs) while a reduced intervention time of 1.5 seconds is more likely to be major (Level 3 HQs).

Padfield, G. D., Manimala, B. and Turner, G.P.

"A SEVERITY ANALYSIS FOR ROTORCRAFT ENCOUNTERS WITH VORTEX WAKES"

Journal of the American Helicopter Society, Vol. 49, No. 4, 2004, pp. 445-457.

The paper concerns the severity of the response of a rotorcraft encountering the vortex of a fixed-wing aircraft. One of the key questions is whether a rotorcraft designed to meet handling performance standards will have sufficient control margin for the pilot to overcome the effects of a vortex encounter. This question is addressed through an analytical study supported by preliminary piloted simulation tests. The handling qualities criteria are found to be well suited to establishing the severity and associated hazard category of typical encounters. Cases are illustrated where insufficient control margin is available to overcome the effects of the encounter. Pilot intervention time is a critical parameter in the upset severity. In risk assessment parlance, an intervention time of 3 seconds leads to hazardous encounters (> Level 3 handling qualities) while with a reduced intervention time of 1.5 seconds, the encounter severity is more likely to be in the major category (Level 3 handling qualities).

Padhy, V. P., Balakrishnan, N. and Murthy, P. S.

"RCS COMPUTATION OF 3D-WAKE VORTEX USING METHOD OF MOMENTS"

Progress in Electromagnetics Research Symposium Proceedings, August 2014, Guangzhou, China, pp. 1319-1322.

An efficient and accurate 3D full wave numerical solution model for computing the radar cross section of wake-vortex is presented, by solving Euler equation to compute the pressure in the aircraft wake region by computational fluid dynamics model and parallel integral equation, based on method of moments is used to compute the volume polarization currents, under the plane wave incidence. Then the currents are used to compute far-field from the vortex region.

Page, R. D.

"THE WAKE VORTEX PROBLEM REVISITED"

Annual Assembly and Technical Symposium Proceedings, Radio Technical Commission for Aeronautics, December 4-6, 1989, pp. 99-123

The FAA Wake Vortex Program and its objectives are presented, with emphasis on new aircraft classification and separation standards, vortex advisory systems and procedures based on vortex behavior, new mechanisms for wake vortex alleviation, wake vortex models, measurement techniques, and user education materials and information. Focus is placed on an enhanced vortex advisory system, including its operational requirements, concept, prototype development and installation, operational evaluation, and specification. It is noted that to enhance the wake vortex system, an airborne Doppler sensor could be developed to locate and evade a wake vortex, and laser Doppler velocimeters could be improved to perform the automatic collection and analysis of wake vortex data. The utilization of the tower- fly-by technique and monostatic acoustic vortex sensing system is assessed.

Page, R. D.

"THE WAKE VORTEX PROBLEM REVISITED"

Proceedings of the 1989 Annual Assembly Meeting and Technical Symposium, RTCA, Washington, DC, 1989, pp. 99-123

There are several possible approaches to be investigated in solving the wake vortex problem; however, the overall objective of the FAA's Wake Vortex Program is to increase airport capacity without a reduction in safety. To accomplish this objective, the following specific activities have been identified. They are: (1) To develop new aircraft classification and separation standards; (2) To develop vortex advisory systems and procedures based on vortex behavior; (3) To update, revise or develop user education materials and information; (4) To develop new mechanisms for wake vortex alleviation; and (5) To develop Wake Vortex models and improve measurement techniques.

Page, R. D., Clawson, K. L., Garodz, L. J. and Rudis, R.

"PANEL DISCUSSION ON TOWER FLY-BY TESTING - 1990 FALL SERIES"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 49-1 - 49-53

In September 1990 the FAA conducted tests at the National Oceanic and Atmospheric Administration (NOAA) Wake Vortex test facility in Idaho to study the wakes of new generation aircraft (B-757, B-767). Also studied were the wakes of a Boeing 727 equipped with smoke generators to enhance flow visualization. The tests were conducted to determine the characteristics of the vortices produced by these new generation aircraft and to see how they might fit into existing or new separation standards. Several measurement techniques and systems were employed to gather the necessary data. Included were: a 200-foot-high tower instrumented with hot film anemometers and meteorological sensors; a laser doppler system; a monostotic acoustic doppler system; a high-resolution anemometer system; and long line sensors. An overview is presented of the techniques and equipment used and preliminary results of the data analyses. Comparisons of B-727 versus B-757 and B-767 wakes are presented. Similar tests were conducted in 1987 using only the tower fly-by technique to study the vortices of the Lockheed C5A/B Galaxy, the C-141B Starlifter and the C-130E Hercules. Pertinent findings from this activity are also presented.

Page, R. D., Rudis, R., Greene, G. C., Machol, R., Tinsley, G., Hergert, C. and Wertz, W.

"PROGRAM PLAN WAKE VORTEX"

DOT/FAA/CT-90/12, May 1990, FAA Technical Center, Atlantic City, NJ

This program plan describes the studies and research which will result in an increase in airport capacity without a reduction in safety. Although earlier programs made progress in several areas, they were terminated before they could significantly impact operations. Due to the need for increased capacity at airports, and in response to recommendations of an industry task force, the Federal Aviation Administration has revitalized its wake vortex research. These revitalized activities are presented in this Wake Vortex Program Plan. The Wake Vortex Program Plan will focus on areas wherein existing knowledge is inadequate and wherein the greatest gains may be possible. Six major activities are addressed: (1) review and analysis of wake vortex research; (2) development of new recommended aircraft classification and separation standards; (3) characterization of wake vortices; (4) development of wake vortex warning systems; (5) vortex alleviation and modification; and (6) updating or development of user educational materials and information. A phased approach will be used, with decision points at the completion of each program phase.

Pailhas, G. and Touvet, Y.

"INSTABILITIES DEVELOPING IN A COUNTER-ROTATING VORTEX PAIR"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

An experimental study was performed to examine the behavior of trailing vortices going down towards the ground and to analyze the instabilities present in their core. A particular attention has been focused on the detection and the characterization of the more unstable large-scale instability. Experiments have been carried out in a tunnel at two reference velocities of 2 m/s and 1.2 m/s respectively for laser and hot-wire measurements. The vortex pair was generated (as Devenport et al.)

by two rectangular wings (NACA0015 section with a chord length c of 0.10 m) facing each other and separated a quarter of chord apart from one another. This leads for the reference velocity 2 m/s to a free stream Reynolds number based on the model chord length of 200,000. Trailing vortex core unsteadiness was clearly pointed out from flow visualizations associated to an adapted image processing technique. The identification of the instabilities mechanisms was undertaken by single and two-point hot-wire measurements. The main feature of this experimental study is the clear identification of the two classes of instability occurring simultaneously in a vortex pair. The characteristic wavelength of both Widnall and Crow instability has been precisely measured. These results permitted to lay the foundations of a strategy of forced vortex reconnection. It is now possible to analyze how the growth of the Crow instability could be affected by an 'external' periodic perturbation applied in the trailing edge region of the wings.

Pailhas, G., Victor, X. and Touvet, Y.

"BEHAVIOUR OF TRAILING VORTICES IN THE VICINITY OF THE GROUND"

10th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 2000

The aim of this experimental study is to analyze the mean velocity field and the turbulence occurring in the core of a counter-rotating vortex pair in the vicinity of the ground. This experiment constitutes the second stage of a previous one the objective of which was to give a general view of a vortex pair close to the wall; it has been conducted in the THALES water tunnel fitted with a moving belt on the test section floor. In this way, the simulation of ground effect has been undertaken. A three-dimensional component laser Doppler Anemometer has been used to measure the three components of the velocity and every component of the Reynolds stress tensor in a YOZ plane perpendicular to the direction of the flow. Measurements in various crosswise planes have been made in sufficiently refined grids allowing a precise description of the vortex flow. The high density of data points obtained in this experiment makes possible the analysis of vorticity and associated circulation fields. It was observed that the axial vorticity was distributed into concentric paths at the first streamwise location; farther downstream, a strong deformation of these iso-contour lines seems to be connected to the movement of the vortex centers when approaching the ground. Another main feature in the evolution of the vortex concerns the turbulence in the core; its constant level is notable whatever the measurement station considered in the streamwise direction. Values as high as 15% indicates that a part of the velocity fluctuations comes probably from the wandering of the vortices. Information, as the orientation of the main shear stress axis in the core, have been gained by investigating contour plots of the joint probability density functions relating to transverse velocity fluctuations and their corresponding correlation. Laser sheet visualizations have been performed to identify the instabilities present in the vortex core.

Paillet, F. L.

"HYDRODYNAMIC STABILITY OF AN AXISYMMETRIC SWIRLING WAKE"

Ph.D. Thesis, June 1974, Rochester University, Rochester, NY

The stability of a superimposed wake and vortex, designed to resemble the far field flow in an aircraft trailing vortex, is investigated using linearized small perturbation theory. Inviscid and viscid stability are both considered. The mean velocity profiles used are the axisymmetric similarity wake for the axial component, and the asymptotic form of the convecting and diffusing vortex (the Lamb vortex) for the swirling component. Radial mean flow is neglected, and profiles are assumed constant over an axial distance much greater than the disturbance wavelength. Stability characteristics are calculated as a function of the ratio of maximum swirling velocity to maximum wake velocity defect for the lowest non-axisymmetric modes.

Paillet, F. L., editor

"PROCEEDINGS OF THE AFFDL/NASA/FAA WAKE TURBULENCE WORK SHOP"

AFFDL-TM-75-16-FGC, September 1974, Flight Dynamics Lab., Wright-Patterson Air Force Base, OH

Summaries of presentations given by ten authorities in the area of wake turbulence are included, along with conclusions on how the present state of wake research relates to USAF operations. Specific attention is paid to wake formation and stability, accident statistics, wind tunnel tests of vortex theories, the simulation of vortex encounter, similarity theory, prediction of vortex encounter severity, and the testing of various vortex dissipation schemes by NASA.

Paireau, O., Tabeling, P. and Legras, B.

"A VORTEX SUBJECTED TO A SHEAR: AN EXPERIMENTAL STUDY"

Journal of Fluid Mechanics, Vol. 351, 1997, pp. 1-16.

The two-dimensional erosion of a vortex subjected to an external, adverse shear is studied experimentally. The flow takes place in a thin stratified layer; the vortex is produced by electromagnetic forcing, whereas the shear is driven mechanically. The system thus allows the vortex strength and the external shear to be controlled independently. We observe the so-called 'erosion' process, i.e. the progressive decrease of the vortex area, leaving the vortex core unaffected. This process is controlled by the ratio $G=S/W$, where W and S are respectively the maximum vorticity of the vortex and the external shear. At small G , the erosion is weak and the vortex survives over the duration of the experiment. At large G , the vortex is first eroded, and then, after a critical time, becomes stretched and eventually breaks up into filaments. During the first period, the compensated maximum vorticity (with friction decay removed) is constant and the vortex area decreases, while beyond the critical time, both quantities decrease with time. A critical value for G , defining the transition between these two regimes, is determined experimentally: $G=0.051 \pm 0.017$. The breaking process itself, during which the vorticity of the vortex core decreases, is investigated. All the qualitative aspects of the erosion process, the onset of breaking and the breaking process itself are found to be in excellent agreement with the theoretical and numerical description. The experimental value of G , and the properties of the filamentation process are consistent with the numerical estimates.

Pakin, A. N.

"TO THE ISSUE ON SELECTING DIFFERENTIAL TURBULENCE MODELS FOR CALCULATING TWO-DIMENSIONAL VORTEX FLOWS"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 90-99

For the conditions of the evolution of an axisymmetric two-dimensional vortex featuring a self-similar tangential velocity profile, a self-similar law of vortex-viscosity distribution within the vortex core has been obtained. The capability is considered of standard variants of three differential turbulence models to describe the stabilizing effect of the vortex swirl in the vortex core and the ways of their modification are proposed. [In Russian.]

Pakin, A. N.

"APPLICATION OF A MODIFIED Q-W TURBULENCE MODEL TO SIMULATION OF TWO-DIMENSIONAL VORTEX GAS MOTION"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 79-92

A modified version of the q-w isotropic eddy viscosity model is proposed, which accounts for a stabilizing effect of flow swirl in the vortex core. By the example of numerical simulation of a vortex pair's evolution in an aircraft's far wake with and out of ground effect, peculiarities are considered of the application of an isotropic eddy viscosity concept of Reynolds stresses in gas vortex motions. In addition, mechanisms of decreasing the total circulation of the core of a vortex in a vortex pair are discussed and the interaction between a vortex pair and the ground boundary layer is analyzed.

Pallek, D. and Klinge, F.

"STUDIES OF REYNOLDS NUMBER EFFECTS ON WING TIP VORTEX POSITIONS BY MEANS OF LASER LIGHT SHEET AND BACKGROUND ORIENTED SCHLIEREN TECHNIQUE UNDER CRYOGENIC CONDITIONS"

New Results in Numerical and Experimental Fluid Mechanics VI, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 96, 2008, pp. 104-112.

The Background Oriented Schlieren Method and the Laser Light Sheet technique were successfully adapted to the cryogenic European Transonic Windtunnel (ETW) and applied to wing tip vortex investigations. Applying optical measurement techniques to ETW is difficult, because of the extreme wind tunnel conditions (temperature, pressure, poor optical access). The near field of a half model of a large modern transport aircraft with landing configuration was investigated at different angles of attack and Reynolds numbers. The results show a small, but significant dependency of the wing tip vortex

position on the Reynolds number for certain angles of attack. The differences are up to 3% of the half-span width.

Panagakos, A. and Lee, T.

"TIP VORTEX CONTROL VIA AN ACTIVE TRAILING-EDGE TAB"

Journal of Aircraft, Vol. 43, No. 4, July-August 2006, pp. 1152-1158

The effect of a movable trailing-edge tab on a tip vortex generated by an oscillating NAC 0015 wing was investigated at $Re = 1.86 \times 100,000$ by using a miniature triple hot-wire probe. Both upward and downward tab deflections, actuated with different start times and durations, were tested. The downward tab motion was most effective in displacing the vortex position. The earlier the actuation the larger the displacement. The upward tab motions were, however, found to be more effective in diffusing the tip vortex and rendered a significantly reduced peak tangential velocity and core circulation, compared to an uncontrolled baseline wing. The earlier and longer the upward tab actuations the lower the vortex core strength and peak tangential velocity. The vortex core radius was rather insensitive to the tab motion. The upward tab deflection, however, produced less induced drag compared to a downward deflection.

Panagiotou, P., Ioannidis, G., Tzivinikos, I. and Yakinthos, K.

"EXPERIMENTAL INVESTIGATION OF THE WAKE AND THE WINGTIP VORTICES OF A UAV MODEL"

Aerospace, Vol. 4, Issue 4, November 2017, pp. 53-1 to 53-17.

An experimental investigation of the wake of an Unmanned Aerial Vehicle (UAV) model using flow visualization techniques and a 3D Laser Doppler Anemometry (LDA) system is presented in this work. Emphasis is given on the flow field at the wingtip and the investigation of the tip vortices. A comparison of the velocity field is made with and without winglet devices installed at the wingtips. The experiments are carried out in a closed-circuit subsonic wind tunnel. The flow visualization techniques include smoke-wire and smoke-probe experiments to identify the flow phenomena, whereas for accurately measuring the velocity field point measurements are conducted using the LDA system. Apart from the measured velocities, vorticity and circulation quantities are also calculated and compared for the two cases. The results help to provide a more detailed view of the flow field around the UAV and indicate the winglets' significant contribution to the deconstruction of wing-tip vortex structures.

Panaras, A. and Voutsinas, S. G.

"EFFECT OF COUNTER-ROTATING VORTICES ON THE DEVELOPMENT OF AIRCRAFT WAKES"

Aeronautical Journal, Vol. 106, Nov. 2004, pp. 585-592.

A two-dimensional vortex particle model is used for studying the development of the vortex wake generated by the wing of an aircraft in the Trefftz plane. Two-dimensional, finite-area vortex structures simulate the initial vorticity distribution at a near-field cross-section of the wing, as provided by either measurements or simulations. The code is used for studying the effect of weak or strong counter-rotating vortices on the development of an aircraft wake. Application in a three-vortex configuration, consisting of the tip and flap vortices, plus a weak negative vorticity sheet lying between them, supports the hypothesis of Graham that the merging of the tip and flap vortices is prevented, because in such an arrangement the counter-rotating vorticity sheet is wrapped around the primary vortices. The present results indicate that even in the far field the tip and flap vortices remain distinct and follow a helical trajectory with large-pitch and small-radius. The code is next applied to the two-vortex system of Savas's triangular wing, in which the circulation of the flap vortex is comparable to that of the tip. Although a 2D analysis is inappropriate for stability analysis it is still useful for a quick qualitative investigation. Results indicate that the flap and tip vortices follow a helical trajectory with large-pitch but also very large radius. During one period, the flap vortex covers a span wise distance equal to the wing span. Such a flow has not been observed in flight or in laboratory tests. Ortega et al, who studied experimentally the triangular wing of O. Savas, found out that before concluding one full spiral, the vortices are literally destroyed (rapid spreading of their vorticity) by an instability mechanism.

Panton, R. L. and Stifle, K. E.

"EXPERIMENTAL STUDY OF A VORTEX SUBJECTED TO IMPOSED STRAIN"

NASA CR-189757, August 1991, Texas Univ. at Austin, Austin, TX

An experimental project was undertaken to investigate the character of vortex breakdown with regard to the waveguide theories of vortex breakdown. A rectangular wing based on the NACA 0012 airfoil was used to produce a trailing vortex which convected downstream without undergoing breakdown. Dye marked the vortex location. A disturbance was then introduced onto the vortex using a small moving wire to 'cut' the vortex. The development of upstream and downstream propagating disturbance waves was observed and the propagation velocities measured. The downstream traveling wave produced a structure similar in appearance to a vortex breakdown. The upstream wave produced a moving, swirling, turbulent region that was not a vortex breakdown. The waves moving in either direction have the same swirl velocity profiles but quite different axial velocity profiles. The upstream disturbance (turbulence) moved into a flow with an axial velocity profile that had a wake-like defect in the core region. The downstream moving vortex breakdown moved into a flow with a jet-like overshoot in the core region. The fact that no breakdown was observed for the wake-like defect and breakdown was observed for the jet-like overshoot is not consistent with computational fluid dynamics (CFD) calculations. Although there are not a lot of examples, CFD results show breakdown for both types of profiles. The longitudinal and swirl velocity profiles were documented by Laser Doppler Velocimeter (LDV) measurement. Wave velocities, swirl angles, and swirl parameters are reported.

Panton, R. L., Oberkampf, W. L. and Soskic, N.

"FLIGHT MEASUREMENTS OF A WING TIP VORTEX"

J. Aircraft, Vol. 17, No. 4, April 1980, pp. 250-259

Detailed flight measurements of the wing tip vortex generated by a DeHavilland Beaver were made with instruments mounted on a sailplane, which was towed behind the aircraft. Data at three different downstream locations were obtained by using three different tow rope lengths. The measurement stations were 4, 8, and 16 span lengths behind the aircraft, and the vortex Reynolds number was slightly above 106. Results of the tests differed considerably from those of previous authors. Although the customary similarity variables for vortex decay were verified, the velocities were a factor of 2.5 higher than previous results. The vortex core radius and turbulence levels also proved to be substantially smaller than earlier measurements. These results indicate that the final similarity state of the vortex may depend strongly upon the initial tip shape, initial turbulence levels of the vortex, and/or the ambient turbulence levels.

Pao, H.-P., Lai, R. Y. and Schemm, C. E.

"VORTEX TRAILS IN STRATIFIED FLUIDS"

Johns Hopkins APL Technical Digest, Vol. 3, Jan.-Mar. 1982, pp. 12-18

A framework is proposed which accounts for the properties of atmospheric vortex trails used by wind flow. Similarities between atmospheric vortex patterns and those in stratified fluids are observed noting that the generation of vortex trails is primarily due to density stratification. Horizontal vortices form for values of Froude numbers between 2-505, and for Reynolds numbers between 600-100,000. The cause of late-wake vortices and the reason for their great regularity is the presence of a large-scale coherent structure in the early wake. A critical Froude number exists above which no horizontal vortices form and its value for a bluff body is about 160. Finally, it is also noted that ambient shear can prevent or destroy late-wake horizontal vortices.

Paoli, R. and Garnier, F.

"INTERACTION OF EXHAUST JETS AND AIRCRAFT WAKE VORTICES: SMALL-SCALE DYNAMICS AND POTENTIAL MICROPHYSICAL-CHEMICAL TRANSFORMATIONS"

C. R. Physique, Vol. 6, 2005, pp. 525-547

This paper summarizes recent progress made in the understanding of the interaction between exhaust jets and trailing vortices in the near field of an aircraft wake. Emphasis is placed on the effects of the jet on the wake vortex dynamics and the effects of the wake on the exhaust dispersion, as well as their potential microphysical and chemical transformations. We discuss in detail results of high-resolution numerical simulations of jet/vortex interaction that include microscale turbulent mixing, gas-phase chemistry, and contrail formation.

Paoli, R. and Shariff, K.

"CONTRAIL MODELING AND SIMULATION"

Annual Review of Fluid Mechanics, Vol. 48, 2016, pp. 393-427.

There is large uncertainty in the radiative forcing induced by aircraft contrails, particularly after they transform to cirrus. It has recently become possible to simulate contrail evolution for long periods after their formation. We review the main physical processes and simulation efforts in the four phases of contrail evolution, namely the jet, vortex, vortex dissipation, and diffusion phases. Recommendations for further work are given.

Paoli, R., Cariolle, D. and Sausen, R.

"REVIEW OF EFFECTIVE EMISSIONS MODELING AND COMPUTATION"

Geoscientific Model Development, Vol. 4, 2011, pp. 643-667.

An important issue in the evaluation of the environmental impact of emissions from concentrated sources such as transport modes, is to understand how processes occurring at the scales of exhaust plumes can influence the physical and chemical state of the atmosphere at regional and global scales. Indeed, three-dimensional global circulation models or chemistry transport models generally assume that emissions are instantaneously diluted into large-scale grid boxes, which may lead, for example, to overpredict the efficiency of NO_x to produce ozone. In recent times, various methods have been developed to incorporate parameterizations of plume processes into global models that are based e.g. on correcting the original emission indexes or on introducing 'sub grid' reaction rates in the models. This paper provides a review of the techniques proposed so far in the literature to account for local conversion of emissions in the plume, as well as the implementation of these techniques into atmospheric codes.

Paoli, R., Helie, J. and Poinso, T.

"CONTRAIL FORMATION IN AIRCRAFT WAKES"

J. Fluid Mech., Vol. 302, 2004, pp. 361-373

The process of the formation and early evolution of a condensation trail ('contrail') in the near field of an aircraft wake was numerically studied by means of a mixed Eulerian/Lagrangian two-phase flow approach. Large-eddy simulations were used for the carrier phase, while, for the dispersed phase, a Lagrangian particle tracking method was used, coupled with a microphysics model to account for ice nucleation. The basic configuration was an exhaust engine jet loaded with soot particles and water vapor and interacting with a wing-tip trailing vortex. The thermodynamic conditions for contrail formation were identified by tracking the spatial distribution of supersaturation around particles. A strong mass coupling between the two phases was demonstrated by the simulations: the condensation

of water vapor over soot particles, induced by exhaust dispersion into cold ambient air, leads to the formation of ice crystals whose size grows until thermodynamic equilibrium between the two phases is reached. Finally, local vapor depletion causes significant deviation from the classical mixing line theory and is also responsible for polydispersion of particle radii.

Paoli, R., Laporte, F. and Cuenot, B.

"DYNAMICS AND MIXING IN JET/VORTEX INTERACTIONS"

Physics of Fluids, Vol. 15, No. 7, July 2003, pp. 1843-1860

This study describes large eddy simulations of the interaction between an exhaust jet and a trailing vortex, in the near-field of an aircraft wake. Two cases are analyzed: in the first one, typical of cruise flight, the jet and the vortex axes are sufficiently well separated to study first the jet dynamics before considering its interaction with the vortex. Dynamics and mixing are controlled both by the jet diffusion and its entrainment around the vortex core. In the second case the jet partially blows in the vortex core, making the flow like a Batchelor vortex. The strong perturbations injected into the core cause an instability of the system which is continuously fed by the jet elements wrapping around the core. This leads to a strong decay of angular momentum and diffusion of the core. Global mixing properties, such as plume area and global mixedness evolutions, are analyzed and two applications to environmental problems are finally discussed.

Paoli, R., Laporte, F. and Cuenot, B.

"JET VORTEX INTERACTIONS IN AIRPLANE WAKES"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

The objective of the present work is to study numerically the interaction between a wing generated vortex and the exhaust jets emitted by the engines, in the near-field of an aircraft wake. We analyzed two different configurations which are representative of the interaction in two and four-engine airplanes in cruise or during approach for landing. In the jet entrainment case, the jet dynamics including transition to turbulence by the Kelvin-Helmoltz instability is simulated, and the mixing characteristics are analyzed. After the jet has become turbulent, a Lamb-Oseen vortex is inserted in an enlarged simulation domain. All flow characteristics have been taken from experimental results. It is shown that the dynamics is mainly governed by the vortex, and that the mixing is greatly enhanced during this second phase. In the blowing jet case, two configurations are investigated. One model configuration consists of a Lamb-Oseen vortex which is superimposed close to the jet. This flow can be interpreted as a q-vortex which is found to amplify helical unstable modes, leading to the transition to turbulence.

Paoli, R., Nybelen, L., Picot, J. and Cariolle, D.

"EFFECTS OF JET/VORTEX INTERACTION ON CONTRAIL FORMATION IN SUPERSATURATED CONDITIONS"

Physics of Fluids, Vol. 25, 2013, pp. 053305-1 to 053305-28.

The effects of the interaction between a model of aircraft trailing vortex and engine jets on the formation of a contrail in supersaturated ambient air are studied using Eulerian-Lagrangian two-phase flows large-eddy simulations. The three-dimensional structure of the contrail, the mean flow properties, and the statistical correlations between ice and water vapor are analyzed for different jet and vortex parameters and different soot particle numbers. The interaction is characterized by the entrainment of the jets by the trailing vortex. In the four-engine case, particles exhausting the outboard jets are exposed to local higher supersaturation due to the temperature drop in the low-pressure vortex core region. The soot particle number affects both the structure and the global characteristics of the contrail. The increase in soot loading results in stronger vapor depletion -- which leads to larger ice production -- and to smaller ice particles for a given amount of vapor exhaust. The fraction of activated particles decreases with soot loading because of the increased competition for the vapor available for condensation. Of particular interest is the interaction between the jet/vortex turbulence and ice microphysics (activation, condensation, particle size distribution, and optical depth). It is found that the characteristic timescales of mixing and condensation can be of the same order in the jet regime. For the present high ambient supersaturation conditions, the competition between the entrainment of humid ambient air and vapor depletion plays an important role in determining the initial growth of the contrail and the spatial and size distributions of ice particles.

Papanikas, D. G., Spyropoulos, A. J., Fertis, D. K. and Margaris, D. P.

"HELICOPTER ROTOR DOWNWASH CALCULATION USING THE VORTEX ELEMENT METHOD FOR THE WAKE MODELLING"

ICAS 1996, September 1996, Sorrento, Napoli, Italy.

This paper presents the calculation of the nonuniform induced downwash of a helicopter rotor in forward flight by utilizing efficient physics-mathematical modeling based on the Vortex Element Method (VEM) for the description of the arbitrary vortex wake, which determines the rotor flowfield. The wake model consists of the concentrated tip vortex, the trailing vortices and the shed vorticity which are discretized into vortex elements. The induced velocity is calculated by means of the Biot-Savart law integration over each of these elements. A computer code has been developed for the calculation of the bound circulation distribution, wake geometry and circulation as well as blade air loading. In the computational procedure the rotor wake contraction and distortion, the vorticity dissipation, the vortex core modeling, the inboard vorticity and wake roll up process are numerically simulated and their influences on the rotor downwash are demonstrated.

Papka, R. J.

"MODELING THE WAKE AS A CONTINUOUS VORTEX SHEET IN A POTENTIAL-FLOW SOLUTION USING VORTEX PANELS"

AFIT/GAE/ENY/89D-26, December 1989, Air Force Institute of Tech., Wright-Patterson AFB, OH

An investigation was made to determine the advantages of modeling the wake as a continuous vortex sheet in an unsteady potential-flow computer model. The existing program modeled the body as a continuous vortex sheet, and modeled the wake as discrete vortex cores employing principles of vortex lattice methods. A method is developed to approximate the wake with triangular vortex panels. The method accounts for redistributing vortex strength as the panels expand and deform. Comparisons are made with results of the original program for a rectangular wing at varying angles of attack. Limited results suggest the method is valid, and areas for further study are recommended.

Paramasivam, S., Poh, C. L. and Schluter, J. U.

"STUDY OF MULTIPLE WAKE VORTEX SYSTEM BEHIND AIRCRAFT NEAR GROUND PROXIMITY USING PRANDTL-LIFTING LINE THEORY"

Tenth International Conference on Computational Fluid Dynamics (ICCFD10), July 2018, Barcelona, Spain.

In this research, a simplified method using Prandtl-Lifting line theory is proposed to model the multiple wake-vortex system shed behind an aircraft in various high-lift lift configurations. It is proven that the spanwise lift distribution has a great effect on the initial structure, strength and number of vortices formed downstream and their evolution. Further, a particular combination of strength and position of flap vortices are found to effectively enhance the secondary vortex formation in the presence of crosswind. This is evident from the plots of Modified landing configuration which has lowest circulation of all configurations. Hence, this proposed method is also helpful in finding out the optimum lift distribution that alleviates the wake-vortex hazard in shorter duration.

Paramasivam, S., Skote, M., Dan, Z. and Schluter, J. U.

"DETAILED STUDY OF EFFECTS OF CROSSWIND AND TURBULENCE INTENSITY ON AIRCRAFT WAKE-VORTEX IN GROUND PROXIMITY"

AIAA Paper 2016-4184, June 2016, Washington, DC.

We present Large-Eddy Simulations of aircraft wake vortices for different crosswind velocities at zero turbulence intensity, and for different turbulence intensities at a crosswind velocity equal to the descent speed of the aircraft wake vortex, to study their impacts on a pair of fully developed wake vortices. The parameters such as circulation, lateral and vertical position of the vortex center, vortex separation distance are investigated with the aid of necessary graphs. Low crosswind velocities are not sufficient to accelerate the decay and push the vortex out of the domain while higher crosswind velocities can intensify the vortex decay earlier and can push the downwind vortex out of the flight path. To have a clear understanding of response of wake-vortices for various crosswind velocities, the slope of lateral movement of vortices with respect to time is represented as a function of crosswind velocity. In addition to the movement, the exit time is also formulated mathematically as a function of crosswind velocity. The effect of lower turbulence intensity levels is found to be insignificant while higher levels have a profound influence on the size of the local secondary vortices formed.

Paredes, P., Rodriguez, D. and Theofilis, V.

"THREE-DIMENSIONAL SOLUTIONS OF TRAILING-VORTEX FLOWS USING PARABOLIZED EQUATIONS"

AIAA Journal, Vol. 51, No. 12, December 2013, pp. 2763-2770.

Flows of practical significance exist, like systems of trailing-vortices, which are inhomogeneous in two directions and weakly dependent along the third spatial direction. Exploiting these characteristics, an integration of the Navier-Stokes equations using the parabolic Navier-Stokes concept is proposed for the recovery of steady solutions that might be used subsequently in the scope of primary instability analyses. The parabolic Navier-Stokes equations are first formulated in a cylindrical coordinate frame and used to calculate the solution of an isolated, axisymmetric nonparallel (axially developing) vortex. Then, the fully three-dimensional flow corresponding to a counter-rotating pair of nonparallel vortices is obtained by parabolic Navier-Stokes formulated in Cartesian coordinates. Stable high-order finite-difference-based numerical schemes are used for the spatial discretization to exploit the benefits of using a sparse direct solver for the inversion of the large matrices resulting from the discretization of the partial-derivative-based parabolic Navier-Stokes equations. Solutions recovered converge to the analytically obtained evolution of an isolated vortex in the limit of large distance between vortices and depart from this idealized situation when the distance becomes of the same order as the radii of the vortices.

Paredes, P., Theofilis, V. and Rodriguez, D.

"PARABOLIC NAVIER-STOKES SOLUTIONS OF TRAILING VORTEX FLOWS"

AIAA Paper No. 2012-3348, June 2012, New Orleans, LA.

Flows of practical significance exist, such as systems of trailing vortices, which are inhomogeneous in two and weakly dependent on the third spatial direction. Exploiting these characteristics, an integration of the Navier-Stokes equations using the Parabolic Navier-Stokes (PNS) concept is appropriate. The PNS equations for vortical systems are first formulated in a Cartesian coordinate frame; the formulation is validated by recovering results for the Blasius boundary layer. Subsequently, a cylindrical coordinate transformation is used to calculate the solution of an isolated non-parallel vortex. Finally, a fully three-dimensional steady laminar flow composed of a counter-rotating pair of non-parallel vortices is obtained by PNS. Stable high-order finite-difference-based numerical schemes are used for spatial discretization to exploit the benefits of using a sparse direct solver for the inversion of the large matrices resulting from the discretization of the partial-derivative based PNS equations. Solutions recovered approach the analytical result in the limit of large distance between vortices, but depart from this idealized situation when the distance becomes of the same order as the radii of the vortices. When the flow swirl parameter is increased, stationary flow instabilities manifest themselves in the obtained solutions.

Park, B H. and Han, Y. O.

"EVOLUTION OF TIP VORTICES GENERATED BY TWO BLADED ROTOR IN HOVER AT EARLY WAKE AGES"

International Journal of Aeronautical and Space Sciences, Vol. 10, No. 2, Nov. 2009, pp. 106-116.

To investigate change of vortex structures and its evolving processes, two dimensional LDV system was used for measurement of velocity vectors of tip vortex, and PIV system was also used for visualizations of tip vortex array for two bladed rotors, respectively. Experiments provided vortex locations, tangential and axial velocity components of tip vortex at six wake ages of 9.5, 10.5, 60.5, 99.5, 129.5, 169.5 and corresponded six wake ages shifted with 180 degrees per each. It was resulted that tip vortices generated by the first blade satisfy Landgrebe's model for their vortex locations even after they were accelerated by the second blade in downstream. Tangential velocity components of tip vortices follow Vatistas' $n=2$ model on both inside and outside regions of rotor slipstream without loss of vortex circulation. Axial velocity profiles revealed that there were small but significant perturbations just outside the primary vortex core which implies the second blade affects the wake substantially. It was also found that tip paths of each blade were not willing to be coincided intrinsically.

Park, K., Seol, H., Choi, W. and Lee, S.

"NUMERICAL PREDICTION OF TIP VORTEX CAVITATION BEHAVIOR AND NOISE CONSIDERING NUCLEI SIZE AND DISTRIBUTION"

Applied Acoustics, Vol. 70, 2009, pp. 674-680.

The tip vortex cavitation behavior and sound generation were numerically analyzed. A numerical scheme combining Eulerian flow field computation and Lagrangian particle trace approach was applied to simulate tip vortex cavitation. Flow field was computed by using hybrid method which combines Reynolds-Averaged Navier-Stokes solver with Dissipation Vortex Model. The trajectory and behavior of each cavitation bubble were computed by Newton's second law and Rayleigh-Plesset equation, respectively. According to nuclei population data, the cavitation nuclei were distributed and convected into the tip vortex flow. Calculated volume of the cavitation bubble and the trajectory were used as the input of cavitation bubble noise analysis. The relationship of cavitation inception, sound pressure level, and cavitation nuclei size was studied at several cavitation numbers. It was found that cavitation inception of smaller nuclei is more sensitive to the change of cavitation number and cavitation noise due to the cavitation smallest nuclei has the most influence on overall tip vortex cavitation noise.

Park, P. S. and Rokhsaz, K.

"EFFECTS OF A WINGLET RUDDER ON LIFT-TO-DRAG RATIO AND WAKE VORTEX FREQUENCY"

AIAA Paper No. 2003-4069, Orlando, FL, June 2003

Computational study of the aerodynamic characteristics of a wing and winglet equipped with a control surface is presented. The wing used for this investigation is similar in design to those employed on business jets. Two aspects of this configuration are studied. The first is the effect of the control surface deflection on the optimum lift-to-drag ratio and its corresponding lift coefficient. The second is

the influence of the control surface deflection on the spiraling frequency in the wake of the winglet. It is demonstrated that any control surface deflection on an otherwise optimized winglet results in reduction of the maximum lift-to-drag ratio. However, the spiraling frequency in the wake of the winglet can be controlled quite well. It is speculated that this type of geometry can be used to exploit the naturally unstable modes of motion of the wake vortex system.

Park, S. O., Kim, J. S. and Lee, B. I.

"HOT-WIRE MEASUREMENTS OF NEAR WAKES BEHIND AN OSCILLATING AIRFOIL"

AIAA Journal, Vol. 28, No. 1, January 1990, pp. 22-28

An experimental investigation was carried out to study the unsteady, near wakes behind an oscillating airfoil. The airfoil was given the harmonic pitching motion about the one-quarter chord axis at two reduced frequencies 0.1 and 0.2. The amplitude of oscillation was 7.4 deg. To assess the effect of mean incidence the mean incidence of oscillation was varied from 0-4 deg. When the mean incidence was 4 deg. the airfoil was found to undergo a deep stall. Streamwise velocity and turbulence intensity profiles were measured by hot-wire anemometry and are presented in the paper. The near-wake measurements made it possible to detect and characterize the emergence of unsteady separation. It was found that the unsteady boundary-layer separation occurred at a greater phase angle (i.e., separation was delayed) when the reduced frequency was greater. When the mean incidence of oscillation was larger, the unsteady separation occurred at a smaller phase angle (i.e., separation was promoted). The linear relationship between the phase angle and the reduced frequency obtained in the present range of the experiment assured us that the characteristic time scale of unsteady separation was the flow time scale given by the ratio of chord length to freestream velocity. Smoke-wire flow visualization was also used to elucidate the link between some of the measured wake data and the various flow states around the airfoil. The phase lag of wake velocity profile relative to the motion of the trailing edge was estimated. The phase lag was found to increase linearly with downstream distance except for the region very near the trailing edge.

Parker, K., Soria, J. and von Ellenrieder, K. D.

"CHARACTERISTICS OF THE VORTEX STREET BEHIND A FINITE ASPECT-RATIO FLAPPING WING"

AIAA Paper No. 2006-1304, Reno, NV, January 2006

Aspects of the evolution of vorticity behind a thrust-producing flapping wing are discussed based on quantitative experiments. Multiple planes of stereoscopic particle image velocimetry measurements are conducted at several locations along the span of a NACA0030-type wing at a Strouhal number of 0.35. Of particular interest is the effect of wingtip vortices on the structure of the flow behind the wing since there is an interrelationship between the wing motion and the flow structure. The spanwise distribution of vorticity is found to be dominated, in the large scale, by a single pair of intense counter-rotating vortices. Over one complete oscillation cycle, the characteristics of the flow in the plane of symmetry is like a reverse Karman vortex street. Each member of the large-scale vortex pair is

constituted by two smaller co-rotating vortices that constructively merge in the initial stages of flow separation. Toward the wingtip the effect of wing three-dimensionality is more significant. The spatio-temporal variations of transverse and spanwise vorticity in these regions suggest severe local flow deformation. Measurements reveal that flow morphology is highly complex and three-dimensional unlike any previously observed, 2D-wing based vortex sheets.

Parkin, P., Holm, R. and Medici, D.

"THE APPLICATION OF PIV TO THE WAKE OF A WIND TURBINE IN YAW"

4th International Symposium on Particle Image Velocimetry, Paper 1154, September 2001, Gottingen, Germany.

PIV has been used in a wind tunnel study of the wake of a 0.25m diameter two bladed model horizontal axis wind turbine (HAWT). Velocity fields of the wake from one to five rotor diameters downstream of the wind turbine model are shown, both with the turbine aligned in the flow and yawed. Data analysis is mainly based on time averaged velocity profiles of the wake for a range of yaw angles $[0 \pm 10, \pm 20, \pm 30]$ in a plane parallel to the flow. Results show the size and persistence of the velocity deficit and tip vortices in the wake, and the wake deflection in yaw. It is shown that active control of turbine yaw angles could be an advantage for overall maximization of power output from wind farms.

Parkinson, Jr., R. C. H. and Kelly, D. W.

"A DYNAMIC ANALYSIS OF AEROPLANES ENCOUNTERING VORTEX WAKE TURBULENCE"

ATN-7301, January 1973, University of Sidney, Sidney, Australia

A six degree of freedom flight simulation model was developed for digital computers to investigate the response of aircraft to a pair of trailing vortices. The model was used to simulate the flight of a light, two-seat training aircraft and a twin-engine commercial transport into the vortices shed by medium weight and heavy weight aircraft.

Parks, E. K., Bach, Jr., R. E. and Shin, J. H.

"RECONSTRUCTION OF THE 1994 PITTSBURGH AIRPLANE ACCIDENT USING A COMPUTER SIMULATION"

J. Aircraft, Vol. 35, No. 5, September-October 1998, pp. 665-670.

On September 8, 1994, a Boeing 737-300 airplane was on a downwind approach to the Pittsburgh International Airport at an altitude of 5000 feet above ground level (6000 feet MSL). While in a shallow left turn onto a downwind approach heading, the airplane crossed into the vortex trail of a B-727 flying in the same approach pattern about 4 miles ahead. The B-737 airplane rolled and turned sharply to the left, exited the vortex wake and plunged into the ground. Weather was not a factor in the accident. The airplane was equipped with a 11+ channel digital Flight Data Recorder (FDR) and a multiple channel

Cockpit Voice Recorder. Both recorders were recovered from the crash site and provided excellent data for the development of an accident scenario. Radar tracking of the two airplanes as well as the indicated air speed perturbations clearly visible on the B-737 FDR recordings indicate that the upset was apparently initiated by the airplane's crossing into the wake of the B-727 flying ahead in the same traffic pattern. A 6 degree-of-freedom simulation program for the B-737 airplane was constructed. The simulation was initialized at the stabilized flight conditions of the airplane about 13 seconds prior to its entry into the vortex trail of the B-727 airplane. By assuming a certain combination of control inputs, it was possible to produce a simulated motion that closely matched that recorded on the FDR.

Parks, E. K., Wingrove, R. C., Bach, R. E. and Mehta, R. S.

"IDENTIFICATION OF VORTEX-INDUCED CLEAR AIR TURBULENCE USING AIRLINE FLIGHT RECORDS"

J. Aircraft, Vol. 22, No. 2, February 1985, pp. 124-129

The nature and cause of clear-air turbulence is being investigated in cooperation with the National Transportation Safety Board, using the flight records available from airline encounters with severe turbulence. This paper presents two case studies of severe turbulence which indicate that the airplanes involved encountered vortex arrays which were generated by destabilized wind-shear layers near the tropopause. In order to identify and analyze vortex patterns (i.e., vortex strength, size, and spacings), potential-flow models of vortex arrays were developed that describe reasonably well the wind patterns derived from the airliner flight records. The results of this analysis indicate that in the two cases studied, the vortex cores had diameters in the range of 900 to 1200 ft. with tangential velocities in the range of 70 to 85 ft./s. This study presents the first identification and analysis of vortex arrays from airline flight data. The results are compared with theoretical predictions and previous observations.

Parks, P. C.

"A NEW LOOK AT THE DYNAMICS OF VORTICES WITH FINITE CORES"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 355-388

The stability theory for wave-like disturbances in a pair of trailing line vortices developed by Crow has been modified to take account of finite core radii and appropriate distributions of vorticity within these cores. The essential features of Crow's theory are confirmed with small numerical changes. The effect of axial flow within the cores may be considered by wrapping the core in a sheath of vortex rings. This model leads to a new stability criterion for a single 'jet-vortex'. The theory, which assumes the vortices extend from infinity to infinity, cannot be used to calculate the growth of perturbations deliberately introduced at the wing of the aircraft, but a modified discretized theory amenable to digital computation has been developed to investigate initial growth of these excited waves.

Parras, L. and Fernandez-Feria, R.

"SPATIAL STABILITY AND THE ONSET OF ABSOLUTE INSTABILITY OF BATCHELOR'S VORTEX FOR HIGH SWIRL NUMBERS"

J. Fluid Mech., Vol. 583, 2007, pp. 27-43

Batchelor's vortex has been commonly used in the past as a model for aircraft trailing vortices. Using a temporal stability analysis, new viscous unstable modes have been found for the high swirl numbers of interest in actual large-aircraft vortices. We look here for these unstable viscous modes occurring at large swirl numbers ($q > 1.5$), and large Reynolds numbers ($Re > 1,000$), using a spatial stability analysis, thus characterizing the frequencies at which these modes become convectively unstable for different values of q , Re , and for different intensities of the uniform axial flow. We consider both jet-like and wake-like Batchelor's vortices, and can analyze the stability for Re as high as 100,000,000. We also characterize the frequencies and the swirl numbers for the onset of absolute instabilities of these unstable viscous modes for large q .

Parrinello, A., Morandini, M. and Mantegazza, P.

"AUTOMATIC EMBEDDING OF POTENTIAL FLOW WAKE SURFACES IN GENERIC MONOLITHIC UNSTRUCTURED MESHES"

Journal of Aircraft, Vol. 50, No. 4, July-August 2013, pp. 1179-1188.

The paper presents two possible ways of modeling wakes within an unstructured two-field potential flow formulation. It aims at avoiding the use of specialized mesh generators featuring the a priori imposition of wake cuts. Thus, by making possible the adoption of widely available general-purpose mesh generators, it gives way to an easier application of a potential formulation to complex configurations. A first approach generates a posteriori wake cuts within generic unstructured meshes, while an alternative method translates the potential discontinuity across the wake into a proper weak constraint on the flow velocity within the grid elements intersected, leaving them unchanged. A steady transonic trim evaluation and a couple of flutter analyses are shown to verify the effectiveness of both strategies, comparing their results with alternative numerical solutions.

Parthasarathy, S. P., Cho, Y. I. and Back, L. H.

"WIDE-FIELD SHADOWGRAPH FLOW VISUALIZATION OF TIP VORTICES GENERATED BY A HELICOPTER ROTOR"

AIAA Paper No. 1985-1557, Cincinnati, OH, July 1985

The vortex trajectory and vortex wake generated by helicopter rotors were visualized using a wide-field shadowgraph technique. Use of a retro-reflective Scotchlite screen made it possible to investigate the flow field generated by full-scale tail rotors. Tip vortex trajectories were visible in shadowgraphs for a range for tip Mach number of 0.38 - 0.60. The effect of the angle of attack was substantial. At an angle of attack greater than 8 degrees, the visibility of the vortex core was significant even at relatively low tip Mach numbers. The theoretical analysis of the visibility was carried out for a rotating blade.

This analysis demonstrated that the visibility decreases with increasing dimensionless core radius and increases with increasing tip Mach number. Based on this investigation, it is concluded that the wide-field shadowgraph flow visualization technique should be feasible to study the flow field generated by a large main rotor in a wind tunnel and in an outdoor full-scale test stand. Of note is that the shadowgraph technique could easily be used with other on-going tests such as aerodynamic performance study, noise measurements, velocity measurements with LDV or hot-wire anemometer, local pressure measurement on the rotor surface, etc.

Pasche, S., Gallaire, F., Dreyer, M. and Farhat, M.

"OBSTACLE-INDUCED SPIRAL VORTEX BREAKDOWN"

Experiments in Fluids, Vol. 55, 2014, pp. 1784-1 to 1784-11.

An experimental investigation on vortex breakdown dynamics is performed. An adverse pressure gradient is created along the axis of a wing-tip vortex by introducing a sphere downstream of an elliptical hydrofoil. The instrumentation involves high-speed visualizations with air bubbles used as tracers and 2D Laser Doppler Velocimeter (LDV). Two key parameters are identified and varied to control the onset of vortex breakdown: the swirl number, defined as the maximum azimuthal velocity divided by the free-stream velocity, and the adverse pressure gradient. They were controlled through the incidence angle of the elliptical hydrofoil, the free-stream velocity, and the sphere diameter. A single helical breakdown of the vortex was systematically observed over a wide range of experimental parameters. The helical breakdown coiled around the sphere in the direction opposite to the vortex but rotated along the vortex direction. We have observed that the location of vortex breakdown moved upstream as the swirl number or the sphere diameter was increased. LDV measurements were corrected using a reconstruction procedure considering the so-called vortex wandering and the size of the LDV measurement volume. This allows us to investigate the spatio-temporal linear stability properties of the flow and demonstrate that the flow transition from columnar to single helical shape is due to a transition from convective to absolute instability.

Pate, D. J. and German, B. J.

"SUPERPOSITION OF SPANWISE CIRCULATION DISTRIBUTIONS: ACCURACY ASSESSMENT AND APPLICATION IN WING DESIGN"

Journal of Aircraft, Vol. 51, No. 5, September-October 2014, pp. 1439-1454.

Superposition of spanwise lift distributions is a familiar concept from lifting-line theory. However, even for linear potential flows, superposition is not rigorously applicable for aerodynamic models and wing geometries in which the shape of the wake vortex system changes with angle of attack. Nonetheless, the influence of these wake effects could generally be expected to be small, insofar as downstream vortices have a weaker influence than the vortex system in the near field of the wing. In this paper, the theoretical framework for lift distribution superposition is first examined. Next, empirical studies conducted with a panel code are presented that show that superposition remains a

very good approximation for a wide range of wing geometries and operating conditions. A method for correcting the small errors in induced drag predictions that result from the application of superposition is also provided. Finally, an application for wing design in which an additional and a design distribution are superposed to produce lift distributions at other operating conditions is presented. This formulation reveals insights into the influence of the design distribution and the planform characteristics, and it supports computationally inexpensive optimization of wing twist.

Paterson, O., Wang, B. and Mao, X.

"COHERENT STRUCTURES IN THE BREAKDOWN BUBBLE OF A VORTEX FLOW"

AIAA Journal, Vol. 56, No. 5, May 2018, pp. 1812-1817.

Helical structures downstream of the breakdown bubble of the Grabowski vortex profile at Reynolds numbers of Re less than or equal to 500 have been extensively studied through stability analyses in the literature. However, the low-frequency coherent structures inside the bubble, which have been observed in experiments, were not predicted by the stability approach. In the present work, asymptotic stabilities of the Grabowski vortex flow at Re less than or equal to 1000 are carried out to compare against previous works, and then the linear optimal inflow perturbation and the corresponding outcome are studied to unveil the dynamics inside the bubble. It is found that low-frequency inflow perturbations penetrate the bubble and are amplified to coherent structures, whereas high-frequency perturbations are convected around the border of the bubble. These linearized results agree well with previous experimental observations and are validated by direct numerical simulations.

Patnaik, B. S. V. and Wei, G. W.

"CONTROLLING WAKE TURBULENCE"

Physical Review Letters, Vol. 88, No. 5, February 2002, pp. 054502-1 - 054502-4. (Erratum, p. 129901-1.)

This Letter introduces a control strategy for taming the wake turbulence behind a cylinder. An angular momentum injection scheme is proposed to synchronize the vertical velocity field. We show that the base suction, wake formation length, absolute instability, and the Karman vortex street are effectively controlled by the angular momentum injection. A control equation is designed to implement the injection. The Navier-Stokes equations, along with the control equation, are solved. The occurrence of a new recirculation free zone is identified.

Patterson Jr, J. C.

"WINGTIP VORTEX TURBINE"

US Patent 4,917,332, April 1990.

A means for extracting rotational energy from the vortex created at aircraft wing tips which consists of a turbine with blades located in the crossflow of the vortex and attached downstream of the wingtip. The turbine has blades attached to a core. When the aircraft is in motion, rotation of core transmits energy to a centrally attached shaft. The rotational energy thus generated may be put to use within the airfoil or aircraft fuselage.

Patterson Jr, J. C. and Flechner, S. G.

"EXPLORATORY WIND-TUNNEL INVESTIGATION OF A WINGTIP-MOUNTED VORTEX TURBINE FOR VORTEX ENERGY RECOVERY"

NASA TP-2468, June 1985, Langley Research Center, Hampton, VA.

An exploratory investigation has been conducted at the Langley Research Center to determine the possibility of recovering, with a turbine-type device, part of the energy loss associated with the lift-induced vortex system. Tests were conducted on a semispan model with an unswept, untapered wing, with and without a wingtip-mounted vortex turbine. Three sets of turbine blades were tested to determine the effect of airfoil section shape and planform. The tests were conducted at a Mach number of 0.70 over an angle-of-attack range of 0 to 4 degrees at a Reynolds number of 3,820,000 based on the wing reference chord of 13 in.

Patterson, Jr., J. C.

"A CONTROLLED METHOD TO OBTAIN A VISUAL HISTORY OF THE LIFT INDUCED WING TIP VORTEX"

LWP-983, August 1971, NASA Langley Research Center, Hampton, VA

Tests were performed in the towing tank facility of the Langley Loads Division. This method of flow visualization is particularly applicable to the study of lift-induced wing tip vortices and has made possible the ability to record the entire life span of the vortex. To accomplish this, a vertical screen of smoke is produced perpendicular to the flight path and allowed to become stationary. The wing panel is then passed through the screen of smoke producing the circular vortex motion which may be recorded by high-speed motion pictures.

Patterson, Jr., J. C.

"LIFT-INDUCED WING-TIP VORTEX ATTENUATION"

AIAA Paper No. 1974-0038, Washington, DC, January 1974

It has been shown by a new static airflow visualization method that a drogue device properly positioned downstream of the wing tip causes vortex breakdown. This same result has been obtained by mounting a jet engine simulator at the wing tip and directing the high-energy jet blast downstream

into the vortex. These configurations, among others, are now under intensive investigation in the new Langley Vortex Research Facility. In this facility a balance mounted vortex generating model is propelled along the 1800-foot track while a second model trailed at 160 feet (scale distance of 1 mile) measures the far-field rolling moment induced by the vortex of the generating model.

Patterson, Jr., J. C.

"VORTEX ATTENUATION OBTAINED IN THE LANGLEY VORTEX RESEARCH FACILITY"

J. Aircraft, Vol. 12, No. 9, September 1975, pp. 745-749

It has been shown by a new static airflow visualization method that a drogue device properly positioned downstream of the wing tip causes vortex breakdown. This same result has been obtained by mounting a jet engine simulator at the wing tip and directing the high-energy jet blast downstream into the vortex. These configurations, among others, are now under intensive investigation in the new Langley Vortex Research Facility. In this facility, a balance mounted vortex generating model is propelled along a 1800-foot track while a second model trailed at 160 feet (scale distance of 1 mile) measures the far-field rolling moment induced by the vortex of the generating model.

Patterson, Jr., J. C.

"UNDERWING COMPRESSION VORTEX ATTENUATION DEVICE"

U.S. Patent 5,230,485, July 1993

A vortex attenuation device is presented which dissipates a lift-induced vortex generated by a lifting aircraft wing. The device consists of a positive pressure gradient producing means in the form of a compression panel attached to the lower surface of the wing and facing perpendicular to the airflow across the wing. The panel is located between the midpoint of the local wing cord and the trailing edge in the chord-wise direction and at a point which is approximately 55 percent of the wing span as measured from the fuselage center line in the spanwise direction. When deployed in flight, this panel produces a positive pressure gradient aligned with the final roll-up of the total vortex system which interrupts the axial flow in the vortex core and causes the vortex to collapse.

Patterson, Jr., J. C. and Flechner, S. C.

"AN EXPLORATORY WIND TUNNEL INVESTIGATION OF THE WAKE EFFECT OF A PANEL TIP-MOUNTED FAN-JET ENGINE ON THE LIFT-INDUCED VORTEX"

NASA TN D-5729, May 1970, NASA Langley Research Center, Hampton, VA

An investigation has been conducted in the Langley 8-foot transonic pressure tunnel to determine the effectiveness of a tip-mounted powered-model high-bypass fan-jet engine in reducing the tip vorticity of an unswept symmetrical panel. The effects of end plates, a body of revolution, and a flow-through nacelle on panel-tip vorticity were also determined for comparison.

Patterson, Jr., J. C. and Jordon, Jr., F. L.

"THRUST-AUGMENTED VORTEX ATTENUATION"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 251-270

An experimental investigation has been conducted in the Langley Vortex Research Facility to determine the vortex attenuating effect of engine thrust. Tests were made using a 0.03-scale model of the Boeing 747 transport aircraft as a vortex-generating model. A Learjet-class probe model was used to measure the vortex-induced rolling moment at a scale separation distance of 1.63 km (0.88 n. mi.). These tests were conducted at a lift coefficient of 1.4 at a model velocity of 30.48 m/s. The data presented in this paper indicate that engine thrust is effective as a vortex attenuating device when the engines are operated at high thrust levels and are positioned to direct the high-energy engine wake into the core of the vortex. The greatest thrust vortex-attenuation is obtained by operating the inboard engine thrust reversers at one-quarter thrust and the outboard engines at maximum forward thrust.

Patterson, Jr., J. C. and Jordon, Jr., F. L.

"A STATIC-AIR FLOW VISUALIZATION METHOD TO OBTAIN A TIME HISTORY OF THE LIFT-INDUCED VORTEX AND CIRCULATION"

NASA TM X-72769, September 1975, NASA Langley Research Center, Hampton, VA.

An investigation of a recently proposed method of flow visualization has been conducted at Langley Research Center. This method of flow visualization is particularly applicable to the study of lift-induced wing tip vortices through which it is possible to record the entire life span of the vortex. To accomplish this, a vertical screen of smoke is produced perpendicular to the flight path and allowed to become stationary. A model is then driven through the screen of smoke producing the circular vortex motion made visible as the smoke is induced along the path taken by the flow and is recorded by high-speed motion pictures.

Patterson, Jr., J. C. and Jordon, Jr., F. L.

"AN INVESTIGATION OF THE INCREASE IN VORTEX INDUCED ROLLING MOMENT ASSOCIATED WITH LANDING GEAR WAKE"

NASA TM X-72786, November 1975, NASA Langley Research Center, Hampton, VA

As part of a NASA-wide program now underway to attempt to reduce the hazard associated with the lift-induced vortex system of large aircraft, a flight test has been conducted at Flight Research Center to verify the results found in the ground base facilities of the effect of span load variation as well as the vortex attenuation of the high energy jet engine exhaust through proper thrust programming. During these flight tests a large increase in vortex strength was experienced because of extending the landing gear. Tests in the Langley Vortex Research Facility indicate that the wake produced by the landing gear

may possibly form an aerodynamic endplate or reflection plane at the inboard edge of each inboard flap which increases the effective aspect ratio of the flap and thereby increases the strength of the flap outer edge vortex.

Patterson, Jr., J. C., Hastings, Jr., E. C. and Jordon, Jr., J. L.

"GROUND DEVELOPMENT AND FLIGHT CORRELATION OF THE VORTEX ATTENUATING SPLINE DEVICE"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 271-304

The data presented in this report indicate that the wing-mounted spline is a effective vortex-attenuating device. A comparison of the vortex-induced rolling moment results at a separation scale distance of 0.70 km (0.38 n. mi.) obtained in the Langley Vortex Research Facility with those measured in full-scale flight indicate good agreement for the unattenuated vortex configuration. The comparison also indicates that the spline effectiveness in flight was greater than in the ground facility test. The results of an applications study show that, for the heavy commercial jet aircraft studied, use of the splines does result in some degradation of the climb gradient and rate of climb, but the aircraft should meet certification requirements.

Pauchet, A., Briancon-Marjollet, L. and Fruman, D. H.

"RECENT RESULTS ON THE EFFECT OF CROSS SECTION ON HYDROFOIL TIP VORTEX OCCURRENCE AT HIGH REYNOLDS NUMBERS"

Cavitation and Multiphase Flow Forum, ASME Vol. 153, 1993, Washigton, DC, pp. 81-86.

Critical cavitation numbers and velocity, axial and tangential, profiles of the tip vortex issued from a 3.8 area ratio elliptical hydrofoil with a NACA0020 cross section at high Reynolds numbers were obtained in the GTH. They are compared with those of a NACA16020 hydrofoil having the same planform. It is shown that for equal experimental conditions, the NACA0020 foil display much larger desinence cavitation numbers as well as larger tangential and axial velocities. The data analysis demonstrates that the modification of the velocity field at the tip of the foil around the vortex, because of the change of the cross section is mainly responsible for most of the observed changes.

Paugam, R., Paoli, R. and Cariolle, D.

"INFLUENCE OF VORTEX DYNAMICS AND ATMOSPHERIC TURBULENCE ON THE EARLY EVOLUTION OF A CONTRAIL"

Atmospheric Chemistry and Physics, Vol. 10, 2010, pp. 3933-3952.

This study describes three-dimensional numerical simulations of the evolution of an aircraft contrail during the first 30 min following the emission of exhausts. The wake is modeled as a vortex pair descending in a stratified atmosphere where turbulent fluctuations are sustained in the late dissipation regime. The focus of the study is laid on the interactions between vortex dynamics, atmospheric

turbulence and contrail microphysics, and their role in determining the growth and the distribution of ice crystals. The atmospheric turbulence is synthesized using a methodology developed to force anisotropic turbulent fluctuations. The results show the feasibility of three-dimensional simulations of the early development of a contrail in supersaturated conditions before its transition into a contrail-cirrus. It is shown that in case of strongly supersaturated and shear-free atmosphere the optical depth is maintained as the contrail spreads by turbulent diffusion in the late dissipation regime.

Pauley, W. R. and Eaton, J. K.

"EXPERIMENTAL STUDY OF THE DEVELOPMENT OF LONGITUDINAL VORTEX PAIRS EMBEDDED IN A TURBULENT BOUNDARY LAYER"

AIAA Journal, Vol. 26, No. 7, July 1988, pp. 816-823

The mean streamwise development of pairs of longitudinal vortices and arrays of longitudinal vortices embedded in an otherwise two-dimensional turbulent boundary layer is studied. Planes of closely spaced measurements of the three components of mean velocity were obtained at several streamwise locations, and the vorticity and circulation were calculated. It was found that the rate of vorticity spreading in a vortex was greatly increased by proximity of other vortices. Vortices remaining close to the wall produced significant levels of spanwise skin friction and, thus, a greater rate of streamwise circulation decrease.

Pavlenko, A. A.

"EFFECT OF THE CALM-ATMOSPHERE STRATIFICATION ON THE EVOLUTION OF AN AIRCRAFT VORTEX WAKE"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 81-89

The process of the entry of a pair of laminar rectilinear vortices into an atmospheric layer with stable stratification is investigated using the numerical solution of the two-dimensional time-dependent Navier-Stokes equations in the Boussinesq approximation. The solution is obtained on a uniform 200 x 200 grid using an explicit finite difference scheme at a flow Reynolds number of $Re = 1,000,000$ for a lapse rate temperature anomaly of 2K per 100 m rise. The calculations have shown that at the initial stage of the submersion of the vortex pair into the stratified layer a deceleration of its descent is observed; during the further descent into the layer the vortices approach one another and their descent rate increases. [In Russian.]

Pavlenko, A. A.

"EVOLUTION OF VORTEX PAIR BEHIND AN AIRCRAFT IN AN ATMOSPHERIC LAYER WITH SIDE SHEAR WIND"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 93-101

A numerical modeling of evolution of a vortex pair in atmospheric layer with side shear wind has been performed. Computational method is based on finite difference solution of the Reynolds averaged two-dimensional unsteady Navier-Stokes equations, with longitudinal component of vorticity and stream function being used as dependent variables. For the system closure the second order differential model of turbulence proposed by Donaldson is used. It was assumed that temperature variation with height corresponds to adiabatic atmosphere (no stratification occurs) and side wind velocity linearly varies with height, i.e., the vortex pair is immersed in a homogeneous field of background vorticity. Flow field parameters (longitudinal component of vorticity and Reynolds stress tensor components) are presented for different moments of time and two values of vertical gradient of side wind velocity. Time dependence of circulation of both the vortices is presented. It is shown that at the peripheral region of the vortex having the same sign of vorticity as that of the background one turbulent pulsation intensity is increased which results in increasing the diffusion of the vortex. The other vortex with the same sign of vorticity as that of the background vorticity varies though slightly.

Pavlenko, A. A.

"INFLUENCE OF THE CALM ATMOSPHERIC STRATIFICATION ON THE EVOLUTION OF THE VORTEX WAKE BEHIND AN AIRCRAFT"

International Science and Technology Center, Moscow, Annual Report, Project 201-95, 1996, pp. 33-40

The process of entrance of a pair of laminar rectilinear vortices into an atmospheric layer with stable stratification is modeled by solving numerically the two-dimensional time-dependent Navier-Stokes equations in Boussinesq's approximation. The solution is obtained on an 200x200 uniform grid using an explicit finite-difference scheme at a flow Reynolds number of $Re=1,000,000$ and a temperature anomaly gradient of 2K per 100m height increment. The computations have shown that at the initial phase of immersion of the vortex pair into the stratified layer, a retardation of their descent is observed, then vortices bring together and the rate of their descent becomes higher.

Pavlin, S., Zuzic, M. and Pavicic, S.

"RUNWAY OCCUPANCY TIME AS ELEMENT OF RUNWAY CAPACITY"

Promet - Traffic & Transportation, Vol. 18, No. 4, 2006, pp. 293-299.

A great many factors determine airside capacity. In the first group are those factors correlated with characteristics of maneuvering areas such as number, layout and location of runways and taxiways. In the following group there are elements correlated with flight operations such as arrival, departure, touch and go operations and the factors related to the aircraft such as weight, separation and wake vortex separation criteria. In the last group there are all other elements such as meteorological conditions and restrictions, ecological conditions, air traffic control skills and equipment, etc. This

paper presents a detailed description of runway occupancy time in arriving and departing flight operations and indications for possible improvements.

Pavlov, V., Buisine, D. and Decossin, S.

"INSTABILITY AND FEATURES OF VORTEX SHEET EVOLUTION"

Comptes Rendus Mecanique, Vol. 330, Issue 11, November 2002, pp. 757-762

The instability and the features of vortex sheet evolution are studied. We consider the self-organization of localized vortices (in two-dimensional flows) into clusters-like and spiral-like structures and show that quasi-final states do not 'forget' conditions of their initial origin. We discuss the physical significance of the obtained results.

Pavlovets, G. A., Voyevodin, A. V. and Zubtsov, A. V.

"ON THE EFFECT OF SPANWISE CIRCULATION DISTRIBUTION ON THE VORTEX WAKE INTENSITY"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 191- 194

This paper considers a possibility to reduce the aircraft vortex wake intensity through redistributing its spanwise circulation, but maintaining the total lift and flight speed.

Peace, A. J. and Riley, N.

"A VISCOUS VORTEX PAIR IN GROUND EFFECT"

J. Fluid Mech., Vol. 129, April 1983, pp. 409-426

We calculate the flow induced by a vortex pair in a viscous fluid, which is otherwise at rest, in the presence of a plane boundary. This may be either a no-slip or a stress-free boundary. The phenomenon of rebound of the vortices from the boundary occurs for either type of boundary, and an explanation for this is offered in terms of viscous effects.

Peebles, J. L.

"EXPERIMENTAL INVESTIGATION OF THE VORTEX STRUCTURE OF A PROTOTYPE V-22 BLADE TIP"

MS Thesis, University of Texas, Arlington, TX, August 1997

The aerodynamic characteristics of an advanced helicopter rotor blade tip were experimentally determined using test conditions typically encountered by rotor tips ($M=0.80$ with $Re=9,800,000$). In the first phase of the test, stagnation pressure surveys of the airfoil wake were performed at two downstream chord stations (0.1 chord and 1.0 chord) and two angles of attack (0 and 3 degrees) using

a wake rake. This yielded preliminary qualitative data in the form of pressure deficits in the wake of the airfoil. Quantitative data about the flow field in the wake were then obtained using a five-hole probe. Data from the probe were used to determine the velocity components in the vicinity of the pressure deficits previously identified. Finally, the lift, drag, and pitching moment coefficients were calculated using data obtained with a five-component sidewall balance.

Peldan, E.

"COMPUTATION OF AIR-VORTICES BASED ON GPU TECHNOLOGY -- OPTIMIZING AND PARALLELIZING A MODEL FOR WAKE-VORTEX PREDICTION USING OPENCL"

MS Thesis, July 2013, Royal Institute of Technology, Stockholm, Sweden.

This thesis details the refinement and numerical solution of a preexisting model for predicting the strengths and positions of so-called wake-vortices that are generated from the lift of heavy aircraft. The ultimate objective is to implement a numerical scheme for the model that is fast enough to allow for probabilistic methods, such as Monte Carlo simulations, to deal with the inherent uncertainty in input parameters for wake-vortex predictions. The differential equation system of the wake-vortex model is stated clearly, which has not been done before. The refinement consists in reducing the number of necessary state variables in the differential equation system. A numerical algorithm based on the mathematical properties of the model is implemented and different ways of optimizing the computations are considered, e.g. through parallelization. Finally, a study will be made trying to assess the validity of the results through analyses of the accuracy and of the model's sensitivity to small input parameter variations.

Pellerin, S. and Giovannini, A.

"INTERACTION VORTEX - BOUNDARY LAYER: NUMERICAL STUDY OF WALL MECHANISMS"

Proceedings of 3rd International Workshop on Vortex Flows and Related Numerical Methods, ESAIM, Vol. 7, 1999, pp. 325-334

The interactions between a coherent vortex structure and a flat plate boundary layer are investigated. The unsteady numerical method used associates the Vortex-In-Cell algorithm for the convection step to the Random Walk algorithm for the diffusion one. The boundary layer is discretized by many vortices, 100,000. An appropriate choice of discretization parameters leads to a good solution for the flat plate and exhibits a minimal numerical dissipation. Interactions are studied for different Reynolds numbers, for positive and negative vortices. The Lighthill's mechanism of production of vorticity is observed. In the case of a negative vortex, a recirculation zone appears and a secondary structure with positive vorticity is created inside the boundary layer. The ejection of this structure induces the rebound of the main vortex.

Pe a, A., Hasager, C. B., Badger, M., Barthelmie, R. J., Bing I, F., Cariou, J-P., ... Wagner, R.

"REMOTE SENSING FOR WIND ENERGY"

Report, DTU Wind Energy-E-Report-0084(EN), March 2016, Roskilde, Denmark.

The Remote Sensing in Wind Energy report provides a description of several topics intended to be the supplemental material to the PhD Summer Schools held at DTU. This is the fourth edition of the report (second externally available). The topics covered ranged from ground based remote sensing principles by optics and acoustics, the physics of the atmospheric boundary layer, atmospheric turbulence, wind profiles from ground based and space-based sensing, as well as power extraction related topics.

Pena, A., Hasager, C. B., Gryning, S.-E., Courtney, M., Antoniou, I. and Mikkelsen, T.

"OFFSHORE WIND PROFILING USING LIGHT DETECTION AND RANGING MEASUREMENTS"

Wind Energy, Vol. 12, 2009, pp. 105-124.

The advantages and limitations of the ZephIR, a continuous-wave, focused light detection and ranging (LiDAR) wind profiler, to observe offshore winds and turbulence characteristics were tested during a 6-month campaign at the transformer/platform of Horns Rev, the world's largest wind farm. The LiDAR system is a ground-based sensing technique which avoids the use of high and costly meteorological masts. Three different inflow conditions were selected to perform LiDAR wind profiling. Comparisons of LiDAR mean wind speeds against cup anemometers from different masts showed high correlations for the open sea sectors and good agreement with their longitudinal turbulence characteristics. Cup anemometer mean wind speed profiles were extended with LiDAR profiles up to 161 m on each inflow sector. The extension resulted in a good profile match for the three surrounding masts. These extended profiles, averaged over all observed stabilities and surface roughness lengths, were compared to the logarithmic profile. The observed deviations were relatively small. Offshore wind farm wakes were also observed from LiDAR measurements where the wind speed deficits were detected at all LiDAR heights. Profile-derived friction velocities and roughness lengths were compared to Charnock's sea roughness model. These average values were found to be close to the model, although the scatter of the individual estimations of sea roughness length was large.

Pena, A., Hasager, C. B., Lange, J., Anger, J., Badger, M., Bingol, F., Bischoff, O., Cariou, J-P., Dunne, F., Emeis, S., Harris, M., Hofsass, M., Karagali, I., Laks, J., Larsen, S., Mann, J., Mikkelsen, T., Pao, L. Y., ... (partial listing)

"REMOTE SENSING FOR WIND ENERGY"

Report, DTU Wind Energy-E-Report-0029(EN), June 2013, Roskilde, Denmark.

The Remote Sensing in Wind Energy report provides a description of several topics intended to be the supplemental material to the PhD Summer Schools held at DTU. This is the third edition of the report (first externally available). The topics covered ranged from ground based remote sensing principles by optics and acoustics, the physics of the atmospheric boundary layer, atmospheric turbulence, wind profiles from ground based and space-based sensing, as well as power extraction related topics.

Peng, D. and Gregory, J. W.

"EXPERIMENTAL STUDY OF VORTEX DYNAMICS DURING BLADE-VORTEX INTERACTIONS"

AIAA Paper 2014-1284, January 2014, National Harbor, MD.

This paper describes the first-phase work of a comprehensive study on vortex dynamics during parallel blade-vortex interaction (BVI). Study of the vortex behavior sheds light on the fundamental interaction mechanism of BVI, and provides important validation data for computational investigations. Evidence has been found in previous studies that the vortex behavior during BVI varies with Reynolds number, but the effects are not clear. In the current study, the relation between Reynolds number and vortex behavior was investigated extensively. The influence of other factors on vortex behavior, such as vortex strength, is also discussed. A pneumatic vortex generation system has been built, which can produce vortices with good repeatability in location, size and strength. The experiment is performed in a low-speed wind tunnel using a planar particle image velocimetry (PIV) technique to characterize the vortex and record BVI incidence. Results indicate that the vortex behavior during BVI strongly depends on the separation distance (h/c) between the vortex and the airfoil. A decrease in vortex strength during BVI is generally observed for h/c less than 0.3. The PIV results also reveal the relation between Reynolds number and the vortex strength variation during the interaction.

Pennings, P. C., Westerweel, J. and van Terwisga, T. J. C.

"FLOW FIELD MEASUREMENT AROUND VORTEX CAVITATION"

Experiments in Fluids, Vol. 56, 2015, pp. 206-1 to 206-13.

Models for the center frequency of cavitating-vortex induced pressure-fluctuations, in a flow around propellers, require knowledge of the vortex strength and vapor cavity size. For this purpose, stereoscopic particle image velocimetry (PIV) measurements were taken downstream of a fixed half-wing model. A high spatial resolution is required and was obtained via correlation averaging. This reduces the interrogation area size by a factor of 2-8, with respect to conventional PIV measurements. Vortex wandering was accounted for by selecting PIV images for a given vortex position, yielding sufficient data to obtain statistically converged and accurate results, both with and without a vapor-filled vortex core. Based on these results, the low-order Proctor model was applied to describe the tip vortex velocity outside the viscous core, and the cavity size as a function of cavitation number. The flow field around the vortex cavity shows, in comparison with a flow field without cavitation, a region of retarded flow. This layer around the cavity interface is like the viscous core of a vortex without cavitation.

Pereira, J. C. F. and Sereno, J.

"UNCERTAINTY QUANTIFICATION OF A 2D VORTEX PAIR IN GROUND EFFECT"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

Stochastic 2D unsteady Navier-Stokes calculations of a vortex pair evolution under ground effect are reported. The numerical procedure is based on the polynomial chaos, representation of the stochastic process. The results include the uncertainty quantification of the 2D velocity field, originated from random perturbations characterized by a uniform Beta pdf and a coefficient of variability equal to 10 percent in the initial vortex circulation and initial vortex position of one of the vortices. The coupled system of equations resulting from the application of the Polynomial Chaos Method of random variables to the NS's requires several modes in the expansion series yielding at least the solution of 8 systems of momentum and continuity equations comprising 24 strongly coupled differential equations. The ensemble of possible solutions (events) will form large clouds of vorticity related to clustered groups of events. This 'mean vorticity' is not a physical quantity but it contains all possible solutions and corresponds to the most probable set of outcomes. The level of variability of the random input chosen is low, nevertheless, it was amplified up 9 times its initial value.

Perez, A. M., Lopez, G. O. D. and Escobar, J. A.

"COMPUTATIONAL STUDY OF THE WAKE OF A QUADCOPTER PROPELLER IN HOVER"

AIAA Paper 2017-3961, June 2017, Denver, CO.

Quadcopter is the main platform for Unmanned Aerial Vehicle (UAV), the use of this technology is growing fast in different industries such as agriculture, mining and oil and gas. Computational Fluid Dynamics (CFD) plays an important role in understanding the aerodynamics of UAVs. In the present paper, the Spalart-Allmaras and k- ω turbulence models were used to simulate a propeller used in a quadcopter in hover. Both models predicted the wake generated by the propeller, as well as thrust and moment coefficients. For validation, numerical results of thrust and torque were compared to experimental measurements based on flying tests. The wake, forces, torque, pressure, and velocity fields predicted by the two turbulence models are similar; the main difference found was in the turbulent viscosity field in the far wake. Both models overestimate thrust and torque around 18 percent, this difference could be due to the interaction of the wakes and with the fuselage that is not included in the present study.

Perez-Batlle, M., Marcos, M. and Pastor, E.

"EFFECTS OF EN-ROUTE WAKE VORTEX ON RPAS OPERATIONS"

Sixth SESAR Innovation Days, November 2016, Delft, The Netherlands.

Compared with common airliners, High/Medium Altitude Long Endurance (HALE/MALE) RPAS are lighter and have larger wingspan. Therefore, RPAS will be extremely sensitive to vortex interactions with larger airliners, not only during departures and arrivals, but also at medium and high altitudes during the enroute phase. The extent of this sensitivity shall be investigated to determine safe levels of separation and come up with feasible maneuvers to avoid the effect of wake vortex under the

assumption that the RPAS may become unrecoverable by the autopilot. For this reason, the objective of this paper is to model the generation of en-route vortex and quantify its impact into the airworthiness of a potentially conflicting RPAS. To accomplish this objective, a wake vortex generation and encounter model will be created as a first step to define the airliner-RPAS separation requirements due to the airliner's vortex. Then, vortex separation requirements will be compared to those usually employed for separation assurance. Conclusion will show that some current separation standards are not conservative enough when the RPAS faces an airliner wake vortex.

Perez-Saborid, M., Herrada, M. A., Gomez-Barea, A. and Barrero, A.

"DOWNSTREAM EVOLUTION OF UNCONFINED VORTICES: MECHANICAL AND THERMAL ASPECTS"

J. Fluid Mech., Vol. 471, 2002, pp. 51-70

We present a numerical study of the downstream evolution (mechanical and thermal) of vortex-jet cores whose velocity and temperature fields far from the axis match a family of inviscid and non-conducting vortices. The far-velocity field is rotational, except for a particular case which corresponds to the well-known Long's vortex. The evolution of the vortex core depends on both the conditions at a certain upstream station, characterized by the dimensionless value of the velocity at the axis, and a dimensionless swirling parameter L defined as the ratio of the values of the azimuthal and axial velocities outside the vortex core. This numerical study, based on the quasi-cylindrical approximation (QC) of the Navier-Stokes equations, determines the conditions under which the vortex evolution proceeds smoothly, eventually reaching an asymptotic self-similar behavior as described in the literature, or breaks in a non-slender solution (vortex breakdown). In particular, the critical value L beyond which vortex breakdown occurs downstream is a function of a dimensionless parameter a characterizing the axial momentum of the vortex jet at an initial upstream station. It is found numerically that for very large values of L , this vortex breakdown criterion tends to an asymptote which is precisely the value predicted by the self-similar analysis, and beyond which a self-similar structure of the vortex core does not exist. In addition, the computation of the total temperature field provides useful information on the physical mechanisms responsible for the thermal separation phenomenon observed in Ranque-Hilsch tubes and other swirling jet devices. In particular, the mechanical work of viscous forces which gives rise to an intense loss of kinetic energy during the initial stages of the evolution has been identified as the physical mechanism responsible for thermal separation.

Peristy, L. H., Perez, R. E. and Jansen, P. W.

"WAKE MODELLING FOR AERIAL REFUELLING USING AERODYNAMIC ADJOINTS"

AIAA Paper 2018-1758, January 2018, Kissimmee, FL.

The modelling of aircraft wakes is of interest for a variety of applications including air-to-air refueling and formation flight, both of which are operational practices that can result in fuel savings. However, aircraft flying in proximity often experience disruptions during flight due to wake turbulence, downwash, and aerodynamic coupling between aircraft. To predict the effect of a tanker aircraft's wake

on the flight dynamics of a refueling aircraft, a coupled vortex lattice method was developed and combined with sensitivity analysis that used an adjoint-based method to quickly predict the change in pitching moment caused by changes in the relative vertical position between the two aircraft. The results from this analysis were compared to existing computational data. Results showed good agreement with trends demonstrated by the existing data in terms of the effect of the tanker aircraft on the lift coefficient and pitching moment coefficient of the refueling aircraft. Differences between models in terms of the value of the tanker's effect on the refueling aircraft were noted. It was thought that these differences were caused by dissimilarities in the tanker models used. The adjoint-based sensitivities were shown to be accurate compared to a finite-difference based approach, but were calculated approximately five times faster. A survey of $d(C_{subm})/dz$ at various points behind a Hercules tanker was presented.

Peristy, L. H., Perez, R. E. and Jansen, P. W.

"WAKE MODELLING WITH EMBEDDED LATERAL AND DIRECTIONAL STABILITY SENSITIVITY ANALYSIS FOR AERIAL REFUELLING OR FORMATION FLIGHT"

AIAA Paper 2019-0583, January 2019, San Diego, CA.

Air-to-air refueling and formation flight are two operational practices that can result in fuel savings. However, aircraft flying in proximity can experience disturbances in terms of aerodynamic forces and moments due to wake turbulence, downwash, and aerodynamic coupling between aircraft. To predict the effect of an aircraft wake on the lateral and directional stability of a trailing aircraft, a coupled vortex lattice method was developed and combined with sensitivity analysis that uses an adjoint-based method to quickly predict the change in rolling moment and yawing moment caused by changes in the relative vertical and lateral position between the two aircraft. A combination of wind-tunnel and flight test data were used as test cases to validate the aerodynamic prediction model and adjoint derived sensitivities. Results showed good agreement with existing data. Regions of static stability were found using the adjoint based sensitivity analysis. These areas of stability were limited to areas where the lateral offset between aircraft was no greater than 40 % of the wingspan. The adjoint-based sensitivities were shown to be accurate when compared to a finite-difference based approach, but were calculated approximately four times faster.

Perkins, E. W. and Canning, T. N.

"INVESTIGATION OF DOWNWASH AND WAKE CHARACTERISTICS AT A MACH NUMBER OF 1.53. I - RECTANGULAR WING"

NACA RM-A8L16, March 1949, Ames Aeronautical Laboratory, Moffett Field, CA.

The results of an experimental investigation of the downwash and wake characteristics behind a rectangular plan-form wing in a supersonic stream are presented. The aspect ratio of the wing was 3.5, and the airfoil section was a 5-percent-thick, symmetrical, double wedge with maximum thickness at 50-percent chord. The tests were made at a Mach number of 1.53 and a Reynolds number, based on

the wing chord length, of approximately 1.25 million. A comparison has been made between the downwash angles predicted by the linear theory and the measured downwash angles predicted by the linear theory and the measured downwash angles. The experimental trends of the variation of downwash angle with angle of attack at zero lift in the spanwise, streamwise, and vertical directions were like those predicted by the linear theory, but in most instances the experimental values were slightly greater than those given by theory. The comparison also showed that the displacement of the vortex sheet and the resulting influence on the downwash distribution must be considered in calculating downwash angles at finite angles of attack. For the low-aspect-ratio wing used in this investigation, the distortion of the vortex sheet behind the wing-tip region had a considerable influence on the position of the wake and on the downwash distribution within a large portion of the induced flow field. In the region outboard of approximately the 30-percent semispan station, the distortion of the vortex sheet decreased the displacement of the sheet considerably from the value calculated by the linear theory.

Perkins, E. W. and Canning, T. N.

"INVESTIGATION OF DOWNWASH AND WAKE CHARACTERISTICS AT A MACH NUMBER OF 1.53. II - TRIANGULAR WING"

RM No. A9D20, June 1949, NACA, Ames Aeronautical Laboratory, Moffett Field, CA.

The results of an experimental investigation of the downwash and wake characteristics behind a triangular plan-form wing in a supersonic stream are presented. The leading-edge sweep angle and aspect ratio were 63 deg and 2.04, respectively. The wing had a 5-percent-thick, symmetrical, double-wedge airfoil section with maximum thickness at 50-percent chord. The tests were made at a Mach number of 1.53 and a Reynolds number, based on the mean aerodynamic chord, of approximately 2 million. Measurements were made of the variation of downwash angle with angle of attack at several positions within the induced flow field. Additional surveys were made to determine the position and extent of the friction wake. These experimental results were analyzed and compared with the characteristics calculated by means of the linear theory. Within that part of the induced flow field where the theory predicts downwash for positive angles of attack of the wing, the experimental values of the variation of the downwash angle with angle of attack through zero lift were found to be in good agreement with the theoretical predictions. Within the remainder of the induced flow field, the agreement was only fair. At angles of attack, appreciably different from zero, the measured downwash angles at the survey points depart markedly from the values predicted by the theory. The reasons for this departure differ in the positive and negative angle-of-attack ranges since the points at which the downwash angles were measured were at a fixed distance above the chord plane of the wing, and the downwash field, at any finite angle of attack, was not symmetric with respect to the extended chord plane. In the positive angle-of-attack range, the departure was primarily the result of the presence of a strong vortex in the induced flow field which was not predicted by the linear theory. In the negative angle-of-attack range, this departure may be attributed to the fact that the displacement of the vortex sheet from the free-stream direction was not as great as predicted by theory. The general characteristics of the friction wake were similar to those observed in subsonic flow. With increasing

distance behind the wing, the wake expanded slowly, decreased in intensity, and with the wing at positive angles of attack, moved downward relative to the free-stream direction.

Perkins, E. W. and Canning, T. N.

"INVESTIGATION OF DOWNWASH AND WAKE CHARACTERISTICS AT A MACH NUMBER OF 1.53. III - SWEPT WINGS"

NACA RM-A9K02, February 1950, Ames Aeronautical Laboratory, Moffett Field, CA.

The results of an experimental investigation of the downwash and wake characteristics behind two highly swept wings in a supersonic stream are presented. The leading-edge sweep angles of the two wings were 63 degrees and 63 degrees 45 minutes, the aspect ratios were 3.50 and 1.66, and the corresponding taper ratios were 0.25 and 1.00. The Mach number of the tests was 1.53 and the Reynolds numbers based on the mean aerodynamic chords were 1.4 million for the tapered wing and 2.6 million for the untapered wing. Measurements were made of the variation of downwash angle with angle of attack at several positions within the induced flow field. Additional surveys were made to determine the position and extent of the friction wake. The experimental downwash results were compared with the characteristics calculated by means of the linear theory. Agreement between the experimental and theoretical values of the rate of change of downwash angle with angle of attack at zero lift was good only at isolated points. In general, the experimental values for the tapered wing were much less than the theoretical. At most of the survey points the rate of change of downwash angle with angle of attack for the tapered wing did not exceed, at any angle of attack, the corresponding theoretical values of the rate of change of downwash at zero lift. The differences between the experimental results for the untapered wing and the theoretical calculations are believed to result from differences between the actual load distribution and that calculated by theory. The general characteristics of the friction wake were like those observed in subsonic flow. With increasing distance downstream from the trailing edge, the wake expanded and, with the wing at positive angles of attack, moved downward relative to the free-stream direction. In general, the maximum pitot-pressure loss at the wake center line decreased with increasing distance behind the trailing edge.

Perkins, S.

"DANGEROUS WAKE"

Science News, Vol. 161, June 2002, p. 387

A new mathematical analysis of an aeronautical hazard known as wake turbulence might eventually lead to improved air safety and increase the number of flights at major airports, scientists say. Using a mathematical model, Saffman and Hill examined how such vortices behave when they encounter wind shear, a natural phenomenon in which adjacent layers of air move at different speeds or in different directions. The researchers found that when the rotation that results opposes an aircraft-trailing vortex, it can cause the vortex to dissipate more quickly than usual. However, when the wind shear

rotates in the same direction as a vortex, the swirl persists longer than it does in the absence of wind shear.

Pern, N. J.

"WAKE VORTEX MITIGATION USING AN ADAPTIVE AIRFOIL"

MS Thesis, 1999, University of Kentucky, Lexington, Kentucky.

In this research, the concept of adaptive airfoils for wake vortex control is explored. Adaptive airfoils are a new area of interest in the field of aerodynamics and aerospace applications. Only recently has this idea become a major concern in the field. There are several concepts of adaptive airfoils in the current literature, but adaptive airfoil development is still in the infancy stage. Previous work done in this area will be briefly outlined and discussed. The idea of fabricating an adaptive airfoil with smart materials will be discussed thoroughly, as well as the potential problems and the future work required in adaptive airfoil development. The specific problem of wake vortex mitigation with adaptive airfoil technology will be addressed.

Pern, N. J. and Jacob, J. D.

"WAKE VORTEX MITIGATION USING ADAPTIVE AIRFOILS: THE PIEZOELECTRIC ARC AIRFOIL"

AIAA Paper No. 1999--524, Reno, NV, January 1999

The development of the vortex wake from a pair of adaptive circular arc airfoils is discussed. A piezo-ceramic actuator with a steel substrate serves as an adaptive airfoil. The baseline (zero potential) radius of curvature R is varied by changing the voltage applied across the arc airfoil. A maximum input voltage varies $R \pm 2\%$ resulting in a maximum change in lift coefficient of approximately 7%. This allows a simple method to examine the effect of unsteady lift coefficient on vortex development and wake mitigation. The application to wake mitigation is explored and preliminary experimental results are discussed. The wing-tip vortex is observed up to 12 chord-lengths downstream for varying frequency.

Perras, G. H. and Dasey, T. J.

"A STATISTICAL ANALYSIS OF APPROACH WINDS AT CAPACITY-RESTRICTED AIRPORTS"

ATC-296, November 2000, MIT Lincoln Lab., Lexington, MA

A study was conducted on six major U.S. airports with closely-spaced parallel (CSP) runways that become capacity-restricted during times of lowered cloud ceilings and visibilities. These airports were SFO, BOS, EWR, PHL, SEA, and STL. Efforts are underway to develop a feasible system for simultaneous CSP approaches, which would increase the capacity at these airports during restrictive weather

conditions. When considering any new procedure, the wind conditions on approach are needed to understand the impact of wake turbulence transport. Wind observations from aircraft that are equipped with Meteorological Data Collection and Reporting System (MDCRS) capabilities were used to conduct a statistical analysis on wind characteristics at each airport. Data from January 1997 through December 1999 were used in each analysis. Data analysis techniques and the statistical results are presented in this report. This information is expected to support procedure and benefits assessment models.

Perras, G. H. and Dasey, T. J.

"A STATISTICAL ANALYSIS OF APPROACH WINDS AT CAPACITY-RESTRICTED AIRPORTS"

19th Digital Avionics Systems Conference, Philadelphia, PA, Vol. 1, Oct. 2000, pp. 3.E.4-1 - 3.E.4-7

Since ambient wind speed and direction are the most important factors when considering the possibility of a lateral wake vortex encounter, wind behavior around airports with closely-spaced parallel (CSP) runways needs to be well understood before simultaneous approaches during restrictive weather could ever be used in an operational setting. This paper presents a statistical analysis of wind behavior for several major airports with CSP runways by using aircraft wind observations. Specifically, speed and direction characteristics of headwinds and crosswinds are examined, as well as correlations between the two wind components with respect to each other and with respect to altitude. The resulting data should prove useful for Monte Carlo simulations of new CSP approach procedures.

Perras, G. H. and Dasey, T. J.

"TURBULENCE CLIMATOLOGY AT DALLAS/FT. WORTH (DFW) AIRPORT - IMPLICATIONS FOR A DEPARTURE WAKE VORTEX SPACING SYSTEM"

NASA/L-4, November 2000, MIT Lincoln Lab., Lexington, MA

Potential adaptive wake vortex spacing systems may need to rely on wake vortex decay rather than wake vortex transport in reducing wake separations. A wake vortex takeoff-spacing system, in particular, will need to rely on wake decay. Ambient turbulence is the primary influence on wake decay away from the ground. This study evaluated 18 months of ambient turbulence measurements at Dallas/Ft. Worth (DFW) Airport. The measurements show minor variation in the turbulence levels at various times of the year or times of the day for time periods when a departure system could be used. Arrival system operation was also examined, and a slightly lower overall turbulence level was found as compared to departure system benefit periods. The Sarpkaya model, a validated model of wake vortex behavior, was applied to various turbulence levels and compared to the DFW turbulence statistics. The results show that wake vortices from Heavy aircraft on takeoff should dissipate within one minute for most of the time and will rarely last two minutes. These results will need to be verified by wake vortex measurements on departure.

Perry, R. B.

"REDUCED SPACING OPERATIONS OVERVIEW"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 5-10

Within NASA's Terminal Area Productivity program, the Reduced Spacing Operations sub element, based at NASA Langley Research Center, is performing research in three airborne areas to enhance airport terminal area capacity throughput. Wake vortex research is underway to build and demonstrate an Aircraft Vortex Spacing System (AVOSS) which will dynamically adjust the spacing between arriving aircraft while preserving or enhancing the current safety level. The design of AVOSS utilizes weather state predictions and real time wake vortex sensing to support both wake vortex transport and demise predictions. Airborne information for Lateral Spacing research is examining instrument approaches to closely spaced parallel runways using cockpit traffic displays and alerting cues. Flight Management System/Center TRACON Automation Center research is addressing the data link of applicable information between the ground and cockpit to enhance the operational efficiency of both.

Perry, R. B.

"NASA AIRCRAFT VORTEX SPACING SYSTEM (AVOSS) RESEARCH"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 25-26

The National Aeronautics and Space Administration (NASA) is addressing airport capacity enhancements during instrument meteorological conditions through the Terminal Area Productivity (TAP) program. Within TAP, the Reduced Spacing Operations (RSO) subelement at Langley Research Center is developing the Aircraft Vortex Spacing System (AVOSS) for use in establishing aircraft arrival scheduling based on dynamic wake vortex spacing criteria. The goal of AVOSS research underway is to develop and demonstrate an engineering model of a dynamic, weather dependent aircraft vortex spacing system, with required lead time and stability considerations, by the year 2000. In today's ATC system, AVOSS could inform ATC controllers when a fixed reduced separation becomes safe to apply to 'large' and 'heavy' aircraft categories. With appropriate integration into the Center/TRACON Automation System (CTAS), AVOSS could provide dynamic spacing tailored to actual generator/follower aircraft pairs rather than a few broad aircraft categories. NASA Langley Research Center recently integrated all the major AVOSS components during the initial field deployment of AVOSS at the Dallas/Fort Worth (DFW) International Airport, and is currently implementing a real-time AVOSS computational capability at NASA Langley to support ongoing real-time meteorological and wake vortex measurements from DFW.

Perry, R. B., Hinton, D. A. and Stuever, R. A.

"NASA WAKE VORTEX RESEARCH FOR AIRCRAFT SPACING"

AIAA Paper No. 1997-0057, Reno, NV, January 1997

The National Aeronautics and Space Administration (NASA) is addressing airport capacity enhancements during instrument meteorological conditions through the Terminal Area Productivity (TAP) program. Within TAP, the Reduced Spacing Operations (RSO) subelement at the NASA Langley Research Center is developing an Aircraft Vortex Spacing System (AVOSS). AVOSS will integrate the output of several inter-related areas to produce weather dependent, dynamic wake vortex spacing criteria. These areas include current and predicted weather conditions, models of wake vortex transport and decay in these weather conditions, real-time feedback of wake vortex behavior from sensors, and operationally acceptable aircraft/wake interaction criteria. In today's ATC system, the AVOSS could inform ATC controllers when a fixed reduced separation becomes safe to apply to 'large' and 'heavy' aircraft categories. With appropriate integration into the Center/TRACON Automation System (CTAS), AVOSS dynamic spacing could be tailored to actual generator/follower aircraft pairs rather than a few broad aircraft categories.

Perry, T. S.

"TRACKING WEATHER'S FLIGHT PATH"

IEEE Spectrum, September 2000, pp. 38-45

Smoother, safer flying is in the forecast for all kinds of weather, thanks to aviation weather technologies now in development. In tackling the problem of turbulence generated behind an aircraft, the wake vortex, the concern is efficiency as well as passenger safety and comfort.

Pete, K. R., Smith, S. T. and Vicroy, D. D.

"MODEL VALIDATION OF WAKE-VORTEX/AIRCRAFT ENCOUNTERS"

AIAA Paper No. 2000-3979, Denver, CO, August 2000

Wake-vortex effects on a 10% scale model of the B737-100 aircraft are calculated using both strip theory and vortex-lattice methods. The results are then compared to data taken in the 30' x 60' wind tunnel at NASA Langley Research Center (LaRC). The accuracy of the models for a reduced geometry, such as with the horizontal stabilizer and the vertical tail removed, is also investigated. Using a 10% error in the circulation strength and comparing the model's results with the experiment illustrates the sensitivity of the models to the vortex circulation strength. It was determined that both strip theory and the vortex lattice method give accurate results when all the geometrical information is used. When the horizontal stabilizer and vertical tail were removed there were difficulties modeling the side force coefficient and pitching moment. With the removal of only the vertical tail unacceptable errors occurred when modeling the side force coefficient and yawing moment. Lift could not be accurately modeled with either the full geometry or the reduced geometry.

Peters, G., Fischer, B. and Kirtzel, H. J.

"ONE-YEAR OPERATIONAL MEASUREMENTS WITH A SONIC ANEMOMETER-THERMOMETER AND A DOPPLER SODAR"

Journal of Atmospheric and Oceanic Technology, Vol. 15, February 1998, pp. 18-28.

A Doppler sodar and an ultrasonic anemometer-thermometer, which are operated continuously at a nuclear research center in Germany, are described. Mean values and second moments including turbulent surface fluxes recorded over 1 yr are analyzed to assess their credibility. Particularly, the effects of rain on the data quality and the statistical bias caused by a reduced data availability -- typical for remote sensing measurements -- are investigated. Mean profiles of the vertical wind variance for different classes of Monin-Obukhov length, the mean vertical wind component versus wind direction, and the annual variation of 24-h averages of the surface heat flux are presented.

Peterson, C. W., Wolfe, W. P. and Payne, J. L.

"EXPERIMENTS AND COMPUTATIONS OF ROLL TORQUE INDUCED BY VORTEX-FIN INTERACTION"

AIAA Paper No. 2004-1069, Reno, NV, January 2004

An experiment was conducted in Arnold Engineering Development Center's 16-ft transonic wind tunnel to measure dependency of vortex-induced counter torque upon J (the ratio of spin motor jet dynamic pressure to freestream dynamic pressure), Mach number, Reynolds number, angle of attack and roll orientation, spin motor nozzle configuration, and fin cant angle. Counter torque data and Laser Vapor Screen images confirm that J is the dominant parameter for correlating counter torque produced by a given vehicle configuration, flight condition, angle of attack and roll orientation. At $M = 0.8$ (with no shock waves in the flow), we observed a monotonic variation of the counter torque coefficient with J that is independent of Reynolds number but dependent on angle of attack and the orientation of the fins with respect to the spin motor nozzle azimuthal location. At $M = 0.95$ and 1.1 , measured values of counter torque coefficient were strongly influenced by changes in Reynolds number, suggesting that shock-boundary layer interaction may be present.

Peterson, R. L., Maier, T., Langer, H. J. and Tranapp, N.

"CORRELATION OF WIND TUNNEL AND FLIGHT TEST RESULTS OF A FULL-SCALE HINGELESS ROTOR"

Aeromechanics Specialists Conference, American Helicopter Society, January 1994, San Francisco, CA, pp. 2.2-1 - 2.2-16.

Correlation of wind tunnel results of a full-scale four-bladed hingeless rotor system with flight test measurements is presented. The results presented are from a recently completed full-scale rotor test in the NASA Ames 40- by 80-Foot Wind Tunnel and a recently completed flight test of a BO-105 helicopter at the DLR, Braunschweig, Germany. Rotor hub and blade loads are shown over a range of

advance ratios from 0.1 to 0.34 for rotor thrust coefficient = 0.07. Good correlation of measured blade root flap bending moments in the wind tunnel with flight test measurements is shown when the rotor is trimmed to measured flight hub pitching and rolling moments. Analytical results using the CAMRAD/JA (Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics, Johnson Aeronautics) analysis shows good correlation when the analysis is trimmed to isolated rotor once-per-revolution root flap moments.

Petitjeans, P., Wesfreid, J. E. and Attiach, J. C.

"VORTEX STRETCHING IN A LAMINAR BOUNDARY LAYER FLOW"

Experiments in Fluids, Vol. 22, 1997, pp. 351-353.

A new technique to produce controlled stretched vortices is presented. The initial vorticity comes from a laminar boundary layer flow and the stretching is parallel to the initial vorticity. This low velocity flow enables direct observations of the formation and destabilization of vortices. Visualizations are combined with quasi-instantaneous measurements of a full velocity profile obtained with an ultrasonic pulsed Doppler velocimeter. Several modes of destabilization are observed and include pairing of two vortices, hairpin deformation, and vortex breakdown into a coil shape.

Petrie, S. L. and Emmer, D. S.

"INVESTIGATIONS OF TRANSONIC TRAILING EDGE FLOWS"

Proceedings of the Second Conf., Soc. for Computer Simulation, San Diego, CA, January 1986, pp. 199-210

An experimental study of several of the trailing edge and wake turbulence properties for a NACA 64A010 airfoil section was completed. The experiments were conducted at the Ohio State University Aeronautical and Astronautical Research Laboratory in the 6-inch x 22-inch transonic wind tunnel facility. The data were obtained at a free stream Mach number of 0.80 and a flow Reynolds number (based on chord length) of 5 million. The principal diagnostic tool was a dual-component laser Doppler velocimeter. The experimental data included surface static pressures, chordwise and vertical mean velocities, RMS turbulence intensities, local flow angles, and a determination of turbulence kinetic energy in the wake at chordwise locations between the transonic shock wave and the trailing edge, in the near wake just downstream of the trailing edge and in the far wake. At the two angles of attack tested (0 and 2 degrees), the turbulence intensities and turbulence kinetic energy were observed to decay in the streamwise direction. In the far wake, for the non-lifting case, the turbulence intensities were nearly isotropic. For the two-degree case, the horizontal component of the turbulence intensity was observed to be substantially higher than the vertical component.

Petry, H. J.

"AN OBJECT-ORIENTED SIMULATION OF THE C-17 WINGTIP VORTICES IN THE AIRDROP ENVIRONMENT"

M.S. Thesis, March 1997, Air Force Inst. of Tech., Wright-Patterson AFB, OH

This thesis effort focuses on the development of an object-oriented simulation of C-17 personnel airdrop operations and provides a tool for risk assessment of jumper and wingtip vortex interaction. Using the initial modeling efforts of the Wright Laboratory, this model expands those efforts to include random aircraft, wind and jumper movement within the simulation using MODSIM 3 as its language. Once the model was built, verified, and calibrated, it helped perform a preliminary analysis of jumper risk with varying element spacing and no crosswind. The results of the simulation provided 15 data points with which linear and logistic regression provided an estimation of the marginal rate of change of jumper/vortex encounter rate. Using the third order model shows that the encounter rate levels off around 24,000 feet spacing between element leaders at 12%, and stays as high as 11% at 32,000 feet before dropping to 0.4% at 34,000 feet. Further research and model improvements may bring the encounter rate down at the more distant spacing but that is left for post thesis analysis efforts.

Pfouts, R. A.

"A COMPARISON BETWEEN SIMULATED AND MEASURED FREE-FLIGHT VORTEX ENCOUNTER BEHAVIOR IN THE NASA LANGLEY FULL-SCALE WIND TUNNEL"

M.S. Thesis, August 1997, Old Dominion University, Norfolk, VA

An examination of the use of static measurements in simulating dynamic aircraft-wake encounters is presented. By comparing dynamic aircraft-wake vortex encounter measurements obtained in free-flight wind tunnel tests to data obtained from computer-simulated encounters based on static wind tunnel data, a determination is made concerning the validity of static vortex models in a dynamic flight environment. The development and testing of specialized elements of a flight simulation code are presented and dynamic free-flight measurements and predicted results are compared. This study shows that static modeling provides reasonable estimates for lateral encounter trajectories when the following aircraft model is farther than one-half its span from the vortex axis. When closer to the vortex axis, dynamic interactions occur between the aircraft model and the vortex that cause the simulator to overpredict the magnitude of vertical and roll accelerations. Although these dynamics interactions are not negligible and their effects cannot be fully estimated by static measurements, reasonable agreement exists between the simulations and the free-flight experiments which justify the use of static models for preliminary estimates of the effects of wake vortex encounters on in-flight operations.

Phillips, E. H.

"NTSB CRASH PROBE FOCUSES ON RUDDER"

Aviation Week & Space Technology, Vol. 142, No. 5, 30 January 1995, pp. 30-31

The U.S. National Transportation Safety Board is increasingly certain that the rudder control system of a Boeing 737-300 contributed to the crash of USAir Flight 427 last September near Aliquippa, Pa. However, tests conducted by Boeing engineers indicate the main rudder power control unit on USAir

Flight 427 was operating normally when the aircraft crashed. The result of a battery of tests and reviews of various possibilities indicated that wake turbulence combined with uncommanded rudder movement may have doomed Flight 427. Simulator tests indicate that a yaw rate of only 2.5 deg/sec is sufficient to cause an initial upset like that recorded by Flight 427. Pilot experts suspect that the rudder was deflected to the left about 15-17 deg throughout the descent.

Phillips, E. H.

"NASA/FAA TO STUDY WAKE VORTEX BEHAVIOR"

Aviation Week & Space Technology, Vol. 141, No. 18, 31 October 1994, p. 70

NASA and the FAA will begin benchmark tests this week at Memphis International Airport to determine if airport capacity can be increased by predicting the behavior and decay of wake vortices. If programs can be developed to accurately and reliably predict the direction and speed of an active vortex as well as when it will decay and cease to be a safety concern, airport capacity could be increased by as much as 12-15%.

Phillips, E. H.

"FAA PROGRAM TARGETS WAKE VORTEX THREAT"

Aviation Week and Space Technology, Vol. 140, No. 7, 14 February 1994, pp. 32, 36

The FAA plans to launch a new, internationally based wake vortex research program this year with the eventual goal of safely reducing aircraft separation standards and increasing airport capacity. The overall goal of the agency's program is to 'provide a scientific understanding of wake vortices' and develop technologies and guidelines to help pilots and air traffic controllers reduce vortex hazards in the airport and en route environments, the plan said.

Phillips, E. H.

"757 WAKE HAZARD CALLED OVERSTATED"

Aviation Week & Space Technology, Vol. 140, No. 6, 7 February 1994, pp. 24-25

The 757's wake signature is no greater than that of other aircraft in its class and requires no change in separation standards, according to FAA and NOAA officials. A report on Boeing 757 wake vortex strength has been 'misinterpreted' and 'no reason' exists to warrant increasing separation standards for aircraft trailing the transports on final approach.

Phillips, E. H.

"VORTEX TESTS MAY YIELD CLUES TO USAIR CRASH"

Aviation Week & Space Technology, Vol. 143, No. 14, 2 October 1995, p. 33.

Still searching for clues in the unsolved mystery of USAir Flight 427, the National Transportation Safety Board is completing wake vortex flight tests that may help investigators learn what caused the Boeing 737-300 to crash near Pittsburgh in September 1994. Initial data indicates that the wake turbulence generated by a 727-200 is more intense than existing computer models predict, and that the vortices are about 50% closer together.

Phillips, N. and Knowles, K.

"POSITIVE AND NEGATIVE SPANWISE FLOW DEVELOPMENT ON AN INSECT-LIKE ROTATING WING"

Journal of Aircraft, Vol. 50, No. 5, September-October 2013, pp. 1321-1332.

This paper presents an experimental investigation of the spanwise flow development on an impulsively started rotating rectangular wing at 45 deg angle of attack. Reynolds numbers of 500 and 15,000 were studied, which correspond to insect and flapping-wing micro-air-vehicle scales, respectively. Stereoscopic particle image velocimetry flowfield measurements were taken at various spanwise locations and sweep angles (angle of rotation from start) on a motor-driven rectangular wing immersed in a seeded water tank. At both Reynolds numbers, the development of the flow was characterized by the formation of strong positive (root-to-tip) and negative (tip-to-root) spanwise flows, which lost strength toward the tip and root, respectively. The negative spanwise flow appeared to be created by the tip vortex, which accelerated fluid from beyond the tip to the root and turned a portion of the positive spanwise flow back on itself, inducing a secondary vortex inboard of the tip vortex and rotating in the opposite sense. Peak positive and negative spanwise flows in both cases were on the order of the wingtip speed. The extent of negative spanwise flow formation on rectangular wings versus tapered wings, as observed in other studies, suggests that perhaps the formation of negative spanwise flow is dependent on wing geometry and the size of the tip vortex.

Phillips, W. F. and Hunsaker, D. F.

"DESIGNING WING TWIST OR PLANFORM DISTRIBUTIONS FOR SPECIFIED LIFT DISTRIBUTIONS"

Journal of Aircraft, Vol. 56, No. 2, March-April 2019, pp. 847-849.

Prandtl's classical lifting-line equation can be used to relate the chord-length distribution, twist distribution, and section-lift distribution for an unswept finite wing. This note presents a general analytic solution such that, given a specified section-lift distribution and either the chord-length distribution or the twist distribution, the third of these distributions can be obtained. If the section-lift distribution and wing planform are specified, the required twist distribution can be found. On the other hand, if the section-lift distribution and wing twist distribution are specified, the required planform can be found. Example solutions are also presented for a case of special interest when designing wings for minimum induced drag. The analytic relations presented in this paper can be used for general wing design and may be particularly useful in the design of morphing wings that can alter

the wing twist distribution and/or planform during flight to obtain optimum lift distributions for various flight phases.

Phillips, W. F., Anderson, E. A., Jenkins, J. C. and Sunouchi, S.

"ESTIMATING THE LOW-SPEED DOWNWASH ANGLE ON AN AFT TAIL"

AIAA Paper No. 2002-0830, Reno, NV, January 2002

A closed-form analytic solution for the downwash induced on an aft tail by the main wing of an airplane is presented. This infinite series solution is based on Prandtl's classical lifting-line theory and accounts for the effects of wing planform shape as well as tail position and vortex rollup. The results obtained from the present analysis reduce to the known solution for an elliptic wing. Results for a tapered wing are also presented. This infinite series solution applies only to a main wing with no sweep or dihedral. However, an approximate correction is presented, which can be used with some caution for swept wings. Results obtained from this analytic solution are compared with other methods and experimental data.

Phillips, W. F., Anderson, E.A., Jenkins, J. C. and Sunouchi, S.

"ESTIMATING THE LOW-SPEED DOWNWASH ANGLE ON AN AFT TAIL"

Journal of Aircraft, Vol. 39, No. 4, July-August 2002, pp. 600-608

A closed-form analytic solution for the downwash induced on an aft tail by the main wing of an airplane is presented. This infinite series solution is based on Prandtl's classical lifting-line theory and accounts for the effects of wing planform shape, as well as tail position and vortex rollup. The results obtained from the present analysis reduce to the known solution for an elliptic wing. Results for a tapered wing are also presented. This infinite series solution applies only to a main wing with no sweep or dihedral. However, an approximate correction is presented, which can be used with some caution for swept wings. Results obtained from this analytic solution are compared with other methods and experimental data.

Phillips, W. R. C.

"TURBULENT PREDICTION AND MEASUREMENT IN A TURBULENT TRAILING VORTEX"

MERLTN 74-5, June 1974, McGill University, Montreal, Canada

The second order closure theory of Launder, Reece and Rodi is used to model the Reynolds stresses in a turbulent trailing vortex. The results are compared with data of a turbulent trailing vortex and are predicted well by the theory.

Phillips, W. R. C.

"THE TURBULENT TRAILING VORTEX DURING ROLL-UP"

J. Fluid Mech., Vol. 105, April 1981, pp. 451-467

The turbulent trailing vortex forming from a rolling-up vortex sheet is considered. The merged region is seen to rapidly attain a state of equilibrium and similarity variables are used to describe it. The detailed distributions of circulation and Reynolds stresses are seen to depend to some extent upon the initial spanwise distribution of circulation on the wing. It is found that two modes of decay of peak tangential velocity are possible depending upon the separation of the vortices.

Phillips, W. R. C.

"THE BOUNDARY LAYER BENEATH A RANKINE-LIKE VORTEX"

Proc. Royal Soc. London, Vol. 411, Series A, May 1987, pp. 177-192

In high lift situations trailing vortices spring from the suction surface of the wing tip, rather like a mini tornado. To simulate this situation, laser doppler anemometry is used to study the flow that results when a Rankine-like vortex rotates normal to a stationary horizontal disc. Measurements are made both in the boundary layer on the surface and in the vortex, which is observed to undergo various types of vortex breakdown.

Phillips, W. R. C.

"ON VORTEX BOUNDARY LAYERS"

Proceedings Royal Society of London, Series A, Vol. 400, August 1985, pp. 253-261.

Flow visualization is used to study the flow that results when a potential vortex rotates normal to a stationary horizontal disc. Close to the disc the vortex is observed to undergo a massive disruption, either of the axisymmetric or helical form. On some occasions the sense of the helix was observed to be opposite that of the outer flow as would be the case with vortex breakdown, while on other occasions it took the same sense as the outer flow.

Phillips, W. R. C. and Graham, J. A. H.

"REYNOLDS-STRESS MEASUREMENTS IN A TURBULENT TRAILING VORTEX"

J. Fluid Mech., Vol. 147, October 1984, pp. 353-371

Measurements of a turbulent trailing vortex in zero pressure gradient are described. These include mean velocities and all the components of the Reynolds-stress tensor. The measurements were made using linearized hot wires at stations 45, 78, and 109 chord lengths downstream of the wing. Axisymmetric jets or wakes were added coaxially to the vortex while the total circulation was held

constant, and their effect studied. It was found that increasing the flow force hastens the radial dispersion of vorticity; this is seen to be concurrent with higher turbulent intensities and Reynolds shear stresses. With the flux of excess axial momentum effectively zero, thereby approximating a turbulent line vortex, no discernable downstream change was observed in the velocity field and very little in the turbulence field. A balance of terms in the mean-momentum equations is presented and discussed. It is seen that, although the radial velocity is numerically much smaller than the axial velocity, terms that contain it, both in axial- and tangential-momentum equations, cannot be ignored, unless the magnitude of the flow force (divided by the fluid density) is much less than the square of the total circulation.

Pichugina, Y. L., Banta, R. M., Brewer, W. A., Lundquist, J. K., Kelley, N. D., Hardesty, R. M., Alvarez, R. J., Mirocha, J. D., Sandberg, S. P. and Weickmann, A. M.

"WIND TURBINE WAKE STUDY BY THE NOAA HIGH-RESOLUTION DOPPLER LIDAR"

16th Coherent Laser Conference, June 2011, Long Beach, CA.

The assessment of the velocity deficit and turbulence associated with operational turbines is a major issue for wind farm design and optimization of the spacing between turbines. The significant velocity deficit and turbulence generated by upstream turbines can reduce the power production and produce harmful vibrations in downstream turbines, which can lead to excess maintenance costs. The complexity of wake effects depends on many factors, both hardware (turbine size, rotor speed, and blade geometry, etc.) and meteorological (prevalent wind direction at the site, wind velocity, wind gradients, boundary layer stability, turbulence characteristics, etc.). A critical issue in addressing these problems is a lack of high-quality measurements, quantitatively characterizing the structure and intensity of turbine-generated wakes and the velocity deficits accompanying them. In this study we use the High-Resolution Doppler Lidar (HRDL), at the Earth System Research Laboratory of NOAA. Over the last decade, HRDL has been used to study flows associated with wind energy, and has a documented capability to observe wakes of obstacles on land, such as trees and buildings, and in water, such as oil platforms and moving ships. This paper will demonstrate HRDL's capability to perform turbine wake measurements. It will present results on wind flow conditions at the experimental site and wind-turbine wake characteristics, such as velocity deficits and downstream extent of wakes.

Picot, J., Paoli, R., Thouron, O. and Cariolle, D.

"LARGE-EDDY SIMULATION OF CONTRAIL EVOLUTION IN THE VORTEX PHASE AND IN INTERACTION WITH ATMOSPHERIC TURBULENCE"

Atmospheric Chemistry and Physics, Vol. 15, July 2015, pp. 7369-7389.

In this work, the evolution of contrails in the vortex and dissipation regimes is studied by means of fully three-dimensional large-eddy simulation (LES) coupled to a Lagrangian particle tracking method to treat the ice phase. In this paper, fine-scale atmospheric turbulence is generated and sustained by means of a stochastic forcing that mimics the properties of stably stratified turbulent flows as those

occurring in the upper troposphere and lower stratosphere. The initial flow field is composed of the turbulent background flow and a wake flow obtained from separate LES of the jet regime. Atmospheric turbulence is the main driver of the wake instability and the structure of the resulting wake is sensitive to the intensity of the perturbations, primarily in the vertical direction. A stronger turbulence accelerates the onset of the instability, which results in shorter contrail descent and more effective mixing in the interior of the plume. However, the self-induced turbulence that is produced in the wake after the vortex breakup dominates over background turbulence until the end of the vortex regime and controls the mixing with ambient air. This results in mean microphysical characteristics such as ice mass and optical depth that are slightly affected by the intensity of atmospheric turbulence. However, the background humidity and temperature have a first-order effect on the survival of ice crystals and particle size distribution, which is in line with recent studies.

Piercy, N. A. V.

"ON THE VORTEX PAIR QUICKLY FORMED BY SOME AEROFOILS"

J. Royal Aeronautical Society, Vol. 27, No. 154, October 1923, pp. 488-500

A study was made on the structure of a vortex in turbulent flow to determine the effect of eddies, if employed in airfoil theory. This study was done because eddies were so commonly found in real flow pass other bodies.

Pierrehumbert, R. T.

"A FAMILY OF STEADY, TRANSLATING VORTEX PAIRS WITH DISTRIBUTED VORTICITY"

J. Fluid Mech., Vol. 99, Pt. 1, July 1980, pp. 129-14.

An efficient relaxation method is developed for computing the properties of a family of vortex pairs with distributed vorticity, propagating without change of shape through a homogeneous, inviscid fluid. The numerical results indicate that a steady state exists even when the gap between vortices is arbitrarily small, and that as the gap closes the steady state approaches a limiting vortex pair with a cusp on the axis of symmetry. Comparison is made with an approximate theory due to Saffman, and agreement is found to be good until the vortices are almost touching. The energy of members of the family is computed, and possible means of experimental production are discussed.

Pierson, K. C. and Povitsky, A.

"VORTICITY CONFINEMENT APPLIED TO TURBULENT WING TIP VORTICES FOR WAKE-INTEGRAL DRAG PREDICTION"

AIAA Paper 2013-2574, June 2013, San Diego, CA.

In the current study the vorticity confinement approach was applied to tip vortices shed by edges of stationary wings to predict induced drag by far-field integration in Trefftz plane. The vorticity

confinement parameter was evaluated first by application to convection of vortices in uniform flow and then to tip vortices shed by finite-aspect ratio rectangular wing in subsonic flight. Dependence of vorticity confinement parameter on the flight Mach number and the angle of attack was evaluated. The aerodynamic drag results with application of vorticity confinement are much closer to analytic lifting line theory compared to integration over surface of wing. While the viscous profile drag is more accurately evaluated by surface integration, the induced drag needs to be evaluated in the far field by applying vorticity confinement to prevent its numerical diffusion by upwind schemes. To apply vorticity confinement to viscous and turbulent flows, it is shown that vorticity confinement does not affect the physical rate of dissipation in viscous/turbulent flows at time scales corresponding to convection of vortices from the wing to Trefftz plane of integration. To account for turbulent effects on tip vortices, vorticity confinement was applied in combination with Spalart-Allmaras, k-e, and six Reynolds stresses models of turbulence.

Piet, J. F., Michel, U. and Bohning, P.

"LOCALIZATION OF THE ACOUSTIC SOURCES OF THE A-340 WITH A LARGE PHASED MICROPHONE ARRAY DURING FLIGHT TESTS"

AIAA Paper No. 2002-2506, June 2002, Breckenridge, CO

Flyover measurements with a phased array of microphones extending over an area of 16 m by 16 m are reported. The 161-microphone array was made possible by combining hardware from ONERA and DLR. In this investigation of the airframe noise of an Airbus A340, the flyover altitudes were between 90 m and 165 m. The data reduction methods for moving objects of DLR and ONERA are compared. Some source maps are shown and discussed. It is demonstrated that nested arrays must be used for a study over a wide frequency range, and that comparisons of the noise maps between different arrays provide valuable information about the noise sources. The ONERA method is shown to be a powerful data reduction method based on a small number of microphones while the DLR method results in alias-free maps at the expense of a much larger number of microphones.

Piggot, B. A. M. and Pask, J. A.

"WAKE VORTEX INCIDENTS REPORTED IN THE UK 1972-1976"

CAA Paper 77012, June 1977, Civil Aviation Authority, London, England

The CAA wake vortex incident reporting scheme was formally initiated in July 1972; reports had previously been collected on an informal basis and reasonably complete information is available on incidents occurring from January 1972 onwards. Pilots who believe their aircraft to have encountered a wake vortex are asked to complete a detailed questionnaire. Whenever possible, the reports are supplemented by spacing data supplied by the air traffic controllers and by meteorological data; this extra information is received as a matter of course when incidents are reported in the neighborhood of London Heathrow airport. In some cases it has been possible to examine flight data recordings from

aircraft involved in reported incidents. An examination is made of the rate of occurrence of incidents before and after the change in separation standards introduced in March 1974.

Pilie, R. J. and Jiusto, J. E.

"A LABORATORY STUDY OF CONTRAILS"

Journal of Meteorology, Vol. 15, April 1958, pp. 149-154.

Contrails were produced for laboratory study by burning aircraft fuels under controlled conditions of ambient temperature and humidity at pressure altitudes between 1000 and 300 mb. Observed critical formation temperatures differ from Appleman's theoretical data in a manner similar to that obtained on project CLOUD TRAIL flights. Laboratory experiments with these trails proved that the initial phase of the condensed moisture is liquid and produced strong evidence that, contrary to general belief, the final phase is sometimes liquid. Additional evidence was obtained indicating that Appleman's criterion for a barely visible trail (0.004 g per cubic meter of condensed moisture) is very nearly correct for ideal conditions of observation such as used in the laboratory, but is probably small by an order of magnitude or more for adverse conditions. By modifying Appleman's theory to allow for the production of a visible quantity of liquid water under adverse viewing conditions, agreement is reached with project CLOUD TRAIL data. Also presented is a simple interpretation of the theory which substantially reduces the labor required to compute critical temperatures for contrail formation.

Pinsker, W. J. G.

"THE HAZARD OF VORTEX WAKE ENCOUNTERS IN THE CRUISE"

TR 79063, June 1979, Royal Aircraft Establishment, Farnborough, England

Records are shown of encounters with vortex wakes of civil aircraft in enroute flight. These are of sufficient severity and frequency to constitute a potential airworthiness hazard. The principal concern is with airframe loads but one case is also documented of a major upset in roll.

Pinton, J.-F. and Brillant, G.

"SOUND AND VORTICITY INTERACTIONS: TRANSMISSION AND SCATTERING"

Theoretical and Computational Fluid Dynamics, Vol. 18, 2005, pp. 413-433

We review several aspects of the propagation of sound in vortical flows. We restrict ourselves to isothermal, humidity-free flows at low Mach number M . Since vorticity plays a major role in vortex-flow interactions we focus on vortical flows. We consider two main canonical situations. The first concerns the transmission of sound. We analyze the evolution of acoustic wavefronts as they propagate across a single vortex. The second situation addresses the scattering of sound waves by nonstationary vortices. We study the evolution of the acoustic pressure emitted in the far field, at an angle with the initial direction of propagation. In this geometry one performs direct spectroscopy of

the flow vorticity field. In each case, we review theoretical results and compare with experimental measurements and numerical simulations when available. We also briefly report how the following new acoustic techniques have recently been used to study complex or turbulent flows: time-resolved acoustic spectroscopy, speckle interferometry and Lagrangian particle tracking.

Pirozzoli, S.

"DYNAMICS OF RING VORTICES IMPINGING ON PLANAR SHOCK WAVES"

Physics of Fluids, Vol. 16, No. 5, May 2004, pp. 1171-1185

In the present paper the encounter of vortex rings with planar shock waves is studied in a three-dimensional environment, with the objective to assess the influence of shock and vortex strength and vortex orientation on the dynamics of the process. The study relies on numerical simulations performed by means of a state-of-the-art hybrid compact/WENO (weighted essentially nonoscillatory) shock-capturing algorithm to solve the Euler equations of gas dynamics. The study focuses on the characterization of the interaction in terms of the evolution of the geometrical parameters of the vortex and the mean flow properties such as kinetic energy and enstrophy. The vortex is compressed as it passes through the shock, and its characteristic dimensions decrease; at the same time its axis is deflected and the ring follows a complex dynamic evolution, even though a nearly steady state is reached for the global quantities. In particular, it has been found that the total vortex kinetic energy is generally nonincreasing after the interaction, while the enstrophy always increases. A simple theory is developed here to shed some light onto the physical phenomena involved, which is found to compare reasonably well with the results of the computations. Some final comments are made regarding the extension of the results reported in the present study to the analysis of shock-compressed turbulence.

Pirrung, G. R., Hansen, M. H. and Madsen, H. A.

"IMPROVEMENT OF A NEAR WAKE MODEL FOR TRAILING VORTICITY"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012083-1 - 012083-10.

A near wake model, originally proposed by Beddoes, is further developed. The purpose of the model is to account for the radially dependent time constants of the fast aerodynamic response and to provide a tip loss correction. It is based on lifting line theory and models the downwash due to roughly the first 90 degrees of rotation. This restriction of the model to the near wake allows for using a computationally efficient indicial function algorithm. The aim of this study is to improve the accuracy of the downwash close to the root and tip of the blade and to decrease the sensitivity of the model to temporal discretization, both regarding numerical stability and quality of the results. The modified near wake model is coupled to an aerodynamics model, which consists of a blade element momentum model with dynamic inflow for the far wake and a 2D shed vorticity model that simulates the unsteady buildup of both lift and circulation in the attached flow region. The near wake model is validated

against the test case of a finite wing with constant elliptical bound circulation. An unsteady simulation of the NREL 5 MW rotor shows the functionality of the coupled model.

Planckaert, L., Coton, P. and Balesdent, M.

"TOOLS FOR DYNAMIC ADJUSTMENT OF AIRCRAFT SEPARATIONS IN WAKE VORTICES"

ICAS Paper 2010-10.2.2, Sept. 2010, Nice, France.

To avoid the risk induced by wake vortices, minimum separation standards between aircraft in the arrival and departure flow have been defined which, nowadays seem to be overly conservative. The aim in the medium / long term of the work presented in this paper is to develop tools for aircraft guidance in the wake turbulence using predictive modelling of the vortices and measurements performed on board or transmitted from outside. Thus, this will enable to perform simulation tests on new operation procedures authorizing more throughput and to give some specifications for new sensors. The proposed avoidance tools are based on the frame of potential field methods, using flatness properties of the flight mechanic model of the aircraft in order to build feasible trajectories.

Plank, V. G. and Spatola, A. A.

"CLOUD MODIFICATION BY HELICOPTER WAKES"

Journal of Applied Meteorology, Vol. 8, August 1969, pp. 566-578.

Helicopter wake effects on stratus and stratocumulus clouds are described. Holes and troughs were created in such clouds with dimensions several hundred feet across. The velocities and penetration distances of the downwash flow beneath the HH-53B helicopter employed in the experiments were investigated by the release of a 'tracing agent' from the helicopter and by hovering at various altitudes above the water surface of a Florida bayou. The downwash velocities were as large as 100 ft/sec, near the rotor, and the downwash extended some 1300 ft beneath the helicopter (under near dry adiabatic conditions). A suggestion is made that helicopters might be employed operationally to clear radiation-type ground fog from airfield runways. The cloud clearing capabilities of the HH-53B helicopter are discussed in support of this suggestion, by reference to observational data and to the theory of Hohler.

Plascott, R. H.

"MEASUREMENTS OF THE PATHS OF THE VORTEX CORES SHED FROM THE WINGS OF A TYPICAL GUIDED-MISSILE MODEL AT $M = 1.57$ "

R. & M. No. 3016, March 1954, Aeronautical Research Council, Great Britain

The paths of the cores of the vortex sheets shed from the wings of a typical guided-missile model, having cruciform rectangular wings mounted on a long cone-cylinder body, have been traced in their movement downstream over a range of incidence and yaw from 5 to 20 deg and 0 to 20 deg respectively at $M = 1.57$. The measurements have shown that: (a) the cores of the vortex sheets

remain close to the plane parallel to the free stream containing the line of the mid-chords of the wings from which the vortex sheets are shed; (b) the movement of the fully rolled-up cores in this plane can, for practical purposes, be attributed entirely to the flow induced by the other wing; (c) estimates of the paths of the vortex cores based on slender-body theory do not agree at all well in the regions investigated owing to the presence of strong shock waves and rapid expansions. Estimates of the paths of the vortex cores based on a semi-empirical analysis have shown reasonable agreement, however, and it is considered that approximations similar to those made in these estimates for this configuration would give reliable values for other configurations in the regions near the wings; well downstream of this region a slender-body theory analysis would probably be satisfactory; (d) slender-body theory gives a reasonable estimate of the spacing of the cores of the fully rolled-up sheets at the zero yaw condition. Estimates of the characteristics of four rear surfaces using this vortex spacing have shown satisfactory agreement with experiment; and (e) further tests to check these conclusions on a large range of missiles seem desirable.

Plassman, G. E., Mall, G. H. and Quagliano, J. R.

"LINEAR MULTIVARIABLE REGRESSION MODELS FOR PREDICTION OF EDDY DISSIPATION RATE FROM AVAILABLE METEOROLOGICAL DATA"

NASA/CR-2005-213504, July 2005, Hampton, VA

Linear multivariable regression models for predicting day and night Eddy Dissipation Rate (EDR) from available meteorological data sources are defined and validated. Model definition is based on a combination of 1997-2000 Dallas/Fort Worth (DFW) data sources. EDR from Aircraft Vortex Spacing System (AVOSS) deployment data, and regression variables primarily from corresponding Automated Surface Observation System (ASOS) data. Model validation is accomplished through EDR predictions on a similar combination of 1994-1995 Memphis (MEM) AVOSS and ASOS data, supplemented with testing using complementary DFW data train and test subsets. Model forms include an intercept plus a single term of fixed optimal power for each of these regression variables; 30-minute forward averaged mean and variance of near-surface wind speed and temperature, variance of wind direction, and a discrete cloud cover metric. Optimal powers are determined by maximizing explained variation during single variable least squares regression. Intercept and term coefficients are then determined by multivariable least squares regression using wind speed variance weighting. Distinct day and night models, regressing on EDR and the natural log of EDR respectively, yield best performance and avoid model discontinuity over day/night data boundaries. Existing AVOSS vortex prediction algorithms may use model predicted EDR from airport specific ASOS data to generate local weather dependent estimates of aircraft wake vortex transport and decay to assess the performance of future wake spacing system concepts. Model-ready, full year 1999 ASOS data for DFW and 11 additional airport sites is prepared for this purpose.

Plougonven, R. and Zhang, F.

"GRAVITY WAVES GENERATED BY JETS AND FRONTS AND THEIR RELEVANCE FOR CLEAR-AIR TURBULENCE"

In *Aviation Turbulence*, edited by R. Sharman and T. Lane, Chapter 19, 2016, Springer International Publishing Switzerland, pp. 385-406.

Jets and fronts are known from observations and modeling studies to be an important source of gravity waves, primarily waves with low intrinsic frequencies. Waves in the jet-exit regions have recurrently been documented and are now rather well understood. Nonetheless, other waves (e.g., involving convection) are also present in the jet/front regions, and there is no simple model available yet to quantitatively predict excited waves from the knowledge of the large-scale flow. Only a handful of case studies have analyzed how jet-generated gravity waves contribute to the occurrence of clear-air turbulence (CAT) in the vicinity of the upper tropospheric jet. They have confirmed that the modulation of vertical shear and stability by strong, low-frequency gravity waves produces localized bands of turbulence. Further studies would be required to discriminate between this and other mechanisms (convectively generated gravity waves, inertial instability) that lead to CAT in the vicinity of jet streaks.

Poisson-Quinton, P. and Werle, H.

"WATER TUNNEL VISUALIZATION OF VORTEX FLOW"

Astronautics and Aeronautics, Vol. 5, June 1967, pp. 64-66

The complexities and subtleties of vortex flow about the wings, fins and fuselage of slender aircraft and missiles have been revealed elegantly by a small water-tunnel. Visualization of the vortices is obtained (1) by colored emissions that show the streamlines near the model and (2) by air-bubbles showing the flow in a thin lighted section either normal or parallel to the flow.

Polentz, P. P.

"COMPARISON OF THE AERODYNAMIC CHARACTERISTICS OF THE NACA 0010 AND 0010-64 AIRFOIL SECTIONS AT HIGH SUBSONIC MACH NUMBERS"

NACA RM A9G19, October 1949, Ames Aeronautical Laboratory, Moffett Field, CA.

A wind-tunnel investigation has been conducted to determine the lift, drag, and pitching-moment characteristics of the NACA 0010 and 0010-64 airfoil sections at Mach numbers up to 0.91 and Reynolds numbers between 1,000,000 and 1,900,000. The results are compared to illustrate the effects of varying the chordwise location of maximum thickness from 30-percent to 40-percent chord on the principal high-speed characteristics of the sections. A virtually unchanged Mach number for lift divergence, a decrease in lift-curve slope of approximately 10 percent, and a reduced maximum lift coefficient at Mach numbers below 0.70 were associated with the more rearward location of maximum thickness. The Mach number for drag divergence was increased about 0.05 at lift coefficients up to 0.4,

but the rate of drag rise above the Mach number for drag divergence was not appreciably changed. Pitching moment was affected to a negligible degree.

Polhamus, E. C.

"CHARTS FOR PREDICTING THE SUBSONIC VORTEX-LIFT CHARACTERISTICS OF ARROW, DELTA, AND DIAMOND WINGS"

NASA TN D-6243, April 1971, NASA Langley Research Center, Hampton, VA.

The leading-edge-suction analogy method of predicting the aerodynamic characteristics of slender delta wings has been extended to cover arrow- and diamond-wing planforms. Charts for use in calculating the potential- and vortex-flow terms for the lift and drag are presented, and a subsonic compressibility correction procedure based on the Prandtl-Glauert transformation is outlined.

Politz, C., Geisler, R. and Ranasinghe, S.

"GROUND BASED LARGE SCALE WAKE VORTEX INVESTIGATIONS BY MEANS OF PARTICLE IMAGE VELOCIMETRY: A FEASIBILITY STUDY"

Advanced In-Flight Measurement Techniques, Research Topics in Aerospace, edited by F. Boden et al, Chapter 17, 2013, Springer-Verlag Berlin Heidelberg, pp. 291-304.

The investigation of aircraft wake vortices is a fundamental challenge in aerospace research. The enhanced safety and efficiency given by better prediction and detection of these complex vortex systems is significant. Within Advanced In-Flight Measurement techniques several non-intrusive optical methods were considered to visualize and measure the wake vortex of a landing aircraft. The main objective of the herewith presented campaign was the application of the Particle Image Velocimetry (PIV) to the investigation of these vortex flows. This report describes the first steps and approaches for the implementation of a large-scale PIV measurement system for the determination of wing wake vortices of a landing aircraft. Many issues have to be addressed before the flyover test could be carried out. During the realization phase of this experiment several steps were considered and discarded, a prototype of a seeding generator based on helium filled soap bubbles was designed and preliminary studies have been carried out exclusively for the investigation of the laser light sheet behavior when propagating over large distances. This report presents a summary of all the considerations and pretests for this application.

Politz, C., Over, B. and Kirmse, T.

"THE APPLICATION OF BACKGROUND ORIENTED SCHLIEREN METHOD TO AIRCRAFT WAKE VORTEX INVESTIGATIONS"

Advanced In-Flight Measurement Techniques, Research Topics in Aerospace, edited by F. Boden et al, Chapter 19, 2013, Springer-Verlag Berlin Heidelberg, pp. 321-329.

Vortex wakes of conventional aircraft and their propagating nature close to the ground have a great impact on the safety and efficiency of the traffic flow on an airport. The development of a measurement technique which helps detecting e.g. the density gradients in the air due to the wake vortices and understanding the nature of such a flow structure in its natural environment can improve the predictability of this hazardous phenomenon. Therefore, the practical aspects of the implementation of an advanced Schlieren technique on an airport are described in this chapter. Two experiments based on slightly different setups and locations relatively to the runway were conducted to access the feasibility of the Background Oriented Schlieren method for the detection and investigation of aircraft wake vortices. The evaluation of the obtained data indicated a sufficient ability of this technique to detect strong density gradient but on the other hand, turned out to be less efficient when dealing with the peculiarities of a large-scale outdoor experiment.

Polsky, S. A. and Miklosovic, D. S.

"CFD STUDY OF BLUFF BODY WAKE FROM A HANGAR WITH COMPARISON TO EXPERIMENTAL DATA"

AIAA Paper No. 2011-3351, June 2011, Honolulu, Hawaii.

The Cobalt V5.0 CFD solver was applied to the prediction of bluff body wake from a model scale hangar configuration at a Reynolds number of 1,600,000. Results were compared against 144th scale surface pressure coefficient and surface oil flow wind tunnel data. Baseline CFD predictions applied a monotone integrated large eddy simulation turbulence modeling approach. Results from delayed detached eddy simulation are also discussed.

Pomeroy, B. W. and Visser, K. D.

"A COMPUTATIONAL STUDY OF INDUCED DRAG BEHAVIOR FOR SPANWISE CAMBERED WINGS"

AIAA Paper No. 2010-4227, June-July 2010, Chicago, Illinois.

Results from lifting line theory, vortex lattice methods, and Euler techniques suggest that simple spanwise cambering of a planar wing, resulting in a reduced projected span but equivalent arc length and area, reduces the induced drag. Lifting line theory suggested a reduction of induced drag in positive cambered wings by almost 1 percent for certain configurations. Three-dimensional Euler flow solutions were obtained using the TetrUSS package from NASA Langley and suggested a drag reduction of as much as 1.6 percent, or 4.3 drag counts for the current configuration, with upward cambered wings. Viscous solutions were also run on the optimum Euler geometry and indicated reduced improvements of less than 1 count or 0.30 percent. Initial optimization with twist improved the Euler results to 2 percent.

Pomin, H. and Wagner, S.

"NAVIER-STOKES ANALYSIS OF HELICOPTER ROTOR AERODYNAMICS IN HOVER AND FORWARD FLIGHT"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 813-821

Reynolds-averaged compressible Navier-Stokes computations are presented for the hovering 7A model rotor and a low aspect ratio NACA0012 rotor in nonlifting forward flight. For enhanced hover performance prediction, aeroelastic effects are considered by tightly coupling the flow solver with a finite element model of the blade based on Timoshenko beam theory. Good agreement between computed and measured rotor performance is achieved for three collective pitch settings on structured periodic grids featuring noncongruent cell faces along the periodicity planes. Results of a hybrid Navier-Stokes/Euler chimera hover computation are presented, in addition to the periodic grid analysis demonstrating the superiority of the overset grid approach with respect to tip vortex conservation. The unsteady Navier-Stokes computations for the nonlifting forward flight test case show more sensitivity relative to time step size than comparable Euler analyses. Overall correlation of computed and experimental near-tip pressure distributions over blade azimuth is fair, and the strong transonic effects on the advancing blade are adequately captured by the numerical analysis.

Pond, S., Smith, S. D., Hamblin, P. F. and Burling, R. W.

"SPECTRA OF VELOCITY AND TEMPERATURE FLUCTUATIONS IN THE ATMOSPHERIC BOUNDARY LAYER OVER THE SEA"

Journal of the Atmospheric Sciences, Vol. 23, Issue 4, July 1966, pp. 376-386.

Measurements of the spectra of fluctuations in wind velocity over the sea sensed by three basically different instruments are described. One comparison shows good agreement between spectra from a thrust anemometer and cup anemometers. Another comparison shows that greatly improved precision of spectra derived from a hot wire anemometer can be gained by calibrating the low frequency response against spectra from cup anemometers. The measurements confirm Kolmogoroff's prediction of the existence of a universal form of the spectrum at high wave numbers. The shape of a spectrum of temperature fluctuations agree with that found by earlier workers.

Ponta, F. L.

"VORTEX DECAY IN THE KARMAN EDDY STREET"

Physics of Fluids, Vol. 22, 2010, pp. 093601-1 - 093601-11.

In this paper, we analyze the effect of viscosity on the vorticity distribution and its rate of decay in the Karman vortex street behind a circular cylinder. We used direct numerical simulation data, which we compare to well-known experimental measurements. By decomposing the incompressible velocity field in a frame of reference attached to the cylinder into its solenoidal and harmonic components, we identify the eddy structure associated with the formation, shedding, and rearrangement of the vortices into the Karman Street, and study their subsequent decay. This allows us to extend the conclusions of the partially viscous model by Hooker, who made several simplifying hypotheses: initial infinite-length filament-vortex wake, circular Lamb vortices of equal age at subsequent times, and no overlapping of vortex cores. We show that the vortices have elliptical cores with an elliptical ratio that evolves

downstream according to a systematic law. We also find that the vortex cores exhibit a Gaussian vorticity profile and a vorticity versus stream-function scatter plot clearly consistent with the Lamb-vortex model. The peak vorticity in the core decays downstream with a hyperbolic decay rate determined by the amount of circulation contained in the core at the early stages of the street, which is also consistent with Lamb's solution.

Pope, S.B. and Whitelaw, J. H.

"THE CALCULATION OF NEAR-WAKE FLOWS"

Journal of Fluid Mechanics, Vol. 73, part 1, 1976, pp. 9-32.

Calculated flow properties are compared with measurements obtained in two-dimensional isothermal wakes with and without recirculation. The equations of continuity and momentum were solved numerically together with equations which formed a turbulence model. Calculations were made using three turbulence models: the first comprised transport equations for turbulence kinetic energy and the rate of turbulence dissipation; the second and third comprised equations for the rate of turbulence dissipation and two forms of Reynolds-stress equations characterized by different redistribution terms. The results show that, for wakes without recirculation, the turbulence model is less important than the boundary condition assumed in the plane of the trailing edge of the body; though the Reynolds-stress models do, of course, provide a better representation of the individual normal stresses. In the case of wakes with recirculation, both the length of the recirculation region and the rate of spread of the downstream wake are underestimated. The second discrepancy is particularly evident and appears to stem from the form of the dissipation equations. A suggestion for improving the modelling of this equation is provided together with necessary justification.

Poppleton, E. D.

"EFFECT OF AIR INJECTION INTO THE CORE OF A TRAILING VORTEX"

J. Aircraft, Vol. 8, No. 8, August 1971, pp. 672-673

The radial distribution of axial velocity which occurs in the wake of any given aircraft depends on the way the vortex is generated, and the overall axial-momentum balance for the fluid that ultimately constitutes the core of the vortex. The note describes preliminary experiments conducted in the McGill 30-inch blower tunnel to examine the possibility that if air is injected along the axis in the early stages of the formation of the vortex, its subsequent behavior may be modified by thus changing conditions in the nascent core. It was found that the effect of blowing through the jet is effectively to 'age' the vortex prematurely.

Poppleton, E. D.

"THE CONTROL OF WING-TIP VORTICES"

Aero. Tech. Note 7102, August 1971, University of Sydney, Sydney, Australia

A device is proposed for the control of the velocity distribution in the core of a trailing vortex. Preliminary calculations show that the required planform shape does not differ radically from that of a conventional wing, and that there is a considerable reduction in vortex drag.

Poppoff, I. G., Farlow, N. H. and Anderson, L. B.

"STUDIES OF AIRCRAFT WAKE CHEMISTRY AND DISPERSION"

Acta Astronautics, Vol. 1, January-February 1974, pp. 157-178

Use of aerospace technology to study aircraft wakes is reviewed. It is shown how aerospace vehicles can be used to provide data for increased understanding of the atmosphere and of aircraft exhaust trails where knowledge is inadequate to evaluate fully the potential impact of the engine emissions. Models of aircraft near-field exhaust wakes are characterized by jet, vortex, and dispersion regimes. Wake growth in the jet regime is self-determined and rapid, whereas further spreading is inhibited in the vortex regime because of circulating vortex motion. Wake diffusion in the dispersion regimes is initially influenced by aircraft induced turbulence but is dominated later by small-scale atmospheric turbulence. Computed fluid mechanical results show the importance of effects such as wake buoyancy, wind shear, turbulence, and traffic corridor exhaust buildup on dispersion of the wake. In the jet regime the exhaust characteristics and thermochemistry serve to illustrate initial chemical changes involving potential pollutant species.

Porter, C. O.

"THE OPTICAL ENVIRONMENT FROM THE TIP VORTICES OF A HELICOPTER IN DIFFERENT FLIGHT REGIMES"

PhD Thesis, October 2011, Notre Dame University, Notre Dame, IN.

Aero-optical aberrations associated with turbulent compressible flow fields can seriously degrade the performance of an optical system; the effect of these aberrations increases as the wavelength of the transiting light becomes shorter, and so is particularly strong at visible and near-infrared wavelengths. These aero-optical aberrations originate from both spatial- and temporal-variations of the index-of-refraction, and are associated with the low-pressure cores and concomitant reduced density within the vortical structures in certain turbulent flow fields such as free-shear layers and tip vortices. To date, aero-optics research has focused primarily on fixed-wing aircraft traveling at compressible-flow speeds, where compressible shear layers and turbulent boundary layers are the dominant source of aero-optic aberrations. Helicopter platforms operate at much lower Mach numbers and are actually best suited for hover. In this case, the optical aberrations produced from shear-layer or turbulent boundary-layer flows are greatly reduced or eliminated in the case of hover; instead, aero-optic aberrations result primarily from the wake of the rotor that can have tip speeds up to a Mach number of one. The tip vortices shed from the rotor blades have an aberrating effect similar to the vortices in a compressible shear-layer that forms behind a turret on a fixed-wing aircraft. In this dissertation, experimental and numerical results

are presented that both calibrate and validate a scaling relationship derived from Euler's equations and the Lamb-Oseen vortex model. Extended numerical simulations of basic helicopter flowfield features were performed for a medium-sized helicopter both in hover and in forward flight to determine estimates of the spatial- and temporal-degradation of a collimated beam traveling through the rotor-blade wake. The results indicate that the severity of the aberration is highly dependent on the vortex circulation strength and core radius. Even with the most conservative estimates, the far field effects of light propagating through these tip vortices greatly reduces the irradiance delivered on target through both tip/tilt and higher order effects. Finally, the use of adaptive optics to correct for these aberrations is examined for the case of hover.

Porter, C., Rennie, M. and Jumper, E.

"THE AERO-OPTICAL ENVIRONMENT OF A HELICOPTER IN FORWARD FLIGHT"

AIAA Paper No. 2011-3283, June 2011, Honolulu, Hawaii.

The performance of an optical system mounted in a hemispherical turret can be seriously limited at certain viewing angles due to aero-optical aberrations on the outgoing beam. The strength of these aberrations is related to the density fluctuations in the air immediately surrounding the turret and is proportional to the Mach number squared; helicopters are therefore an attractive platform for optical systems due to their low flight speeds. In this case, aero-optical aberrations can still arise, however, from the wake and especially the tip vortices from the helicopter blades. A simplified model of a rotor tip-vortex is used to gain insight into the potential aero-optical environment of a helicopter in forward flight. The simplified model allows for the rapid calculation of aero-optic effects at different forward-flight speeds. The results indicate that the largest aero-optic aberration originates from 'super vortices' that appear along the lateral edge of the helicopter wake. Estimated aberration amplitudes are presented, as well as an estimate of the undisturbed viewing angle of the optical system as a function of forward-flight speed.

Porter, C., Rennie, M. and Jumper, E.

"AERO-OPTIC EFFECTS OF A WINGTIP VORTEX"

AIAA Journal, Vol. 51, No. 7, July 2013, pp. 1533-1541.

For an optical system carried by a helicopter, aero-optic aberrations originate primarily from blade tip vortices that pass through the system field of view. These aberrations result from the reduced pressure and density in the vortex cores, and the associated variations in the index of refraction. As part of an investigation into the full aero-optic environment surrounding a helicopter, this paper describes an investigation into the optical character of a single tip vortex. The Lamb-Oseen vortex model is used to compute realistic velocity fields, which are then used with the energy equation to determine thermodynamic properties. The resulting aero-optic data are used to calibrate a scaling law that is derived from the basic fluid-mechanic equations of motion, and this scaling law is validated against

experimental data. The scaling relationship is then used to make a simple estimate of the vortex-induced aberrations on a fuselage-mounted optical system for a medium-sized helicopter.

Porter, C., Rennie, M. and Jumper, E.

"COMPUTATION OF THE AERO-OPTICAL ENVIRONMENT OF A HELICOPTER USING PRESCRIBED-WAKE METHODS"

AIAA Journal, Vol. 53, No. 3, March 2015, pp. 532-541.

A fast low-order computational approach is presented for estimating the aero-optic effect of the rotor tip vortex system on helicopter-borne optical systems. The approach employs prescribed-wake methods that have been developed by the helicopter design community to rapidly generate realistic approximations to the vortex-wake systems of helicopters in hover and forward flight. With the geometry of the vortex-wake system defined, an experimentally validated computational method that employs the isentropic assumption is then used to compute pressure, temperature, density, and index-of-refraction fields in the selected computational domain. Predictions determined using the computational approach for the spatially and temporally resolved aero-optic aberrations on an optical system mounted on a helicopter in hover and forward flight are presented.

Portnoy, H.

"THE EFFECT OF WAKE THICKNESS ON THE ROLLING-UP PROCESS IN TWO DIMENSIONS"

ICAS 1976, October 1976, Ottawa, Ontario, Canada.

A numerical method is developed for calculating the flow field due to a two-dimensional distribution of vorticity over a given area. A distribution of vorticity over a long thin ellipse is then used to model the flow about the unrolled cross-section of a thick wake far downstream of the wing trailing-edge. The distribution is now allowed to distort under the action of its own induced velocity field, (which is calculated by the aforementioned numerical method), thus simulating roll-up of a wake with thickness. The influence of viscosity is neglected and two different span loadings are studied.

Portnoy, H.

"AERODYNAMIC EFFECTS OF VORTEX SUPPRESSORS"

TAE-221, July 1974, Technion-Israel Inst. of Technology, Haifa, Israel

The effectiveness of various devices in accelerating the dissipation of wing-tip vortices has received considerable attention recently. These devices include jets blown into or near the vortex core, both in the upstream and downstream direction, small cruciform wings, both fixed and rotating, mounted close behind the wing near tip and angled fences or vortex generators mounted on the wing upper and lower surfaces so as to produce swirl opposite to that of the tip vortex. In this report are proposed

mathematical models for representing some of these devices in order to calculate their effects on the wing aerodynamic properties.

Portnoy, H.

"CALCULATION OF THE AERODYNAMIC EFFECTS OF CERTAIN VORTEX SUPPRESSING DEVICES"

AFOSR-TR-75-0713, December 1974, Technion-Israel Inst. of Technology, Haifa, Israel

There has been a recent increase of interest in devices for accelerating the dissipation of wing-tip trailing vortices. A number of experimental programs have been carried out to determine the effectiveness of various devices, such as tip-mounted jets, small windmills, suitably disposed vortex generators and so on, in increasing the rate of vortex decay. Only limited attention seems to have been paid to the effects of these devices on the wing aerodynamic properties and the work that has been done appears to be entirely experimental. It is the purpose of the present paper to propose three simple mathematical models which may be used to assess many of the current suppressors, from the viewpoint of wing property modification.

Portnoy, H.

"THE INITIAL ROLL-UP OF A THICK, TWO-DIMENSIONAL WAKE BEHIND A WING OF FINITE SPAN"

TAE-262, November 1975, Technion-Israel Inst. of Technology, Haifa, Israel.

This work is an attempt to remove the unrealistic features of earlier vortex wake models, namely zero wake thickness and vorticity concentrated on lines, by assuming that the wake vorticity is contained in a layer of finite thickness with some plausible cross-sectional shape. The wake flow is assumed to be two-dimensional and the rolling-up is studied via the time-dependent development of this model so that it deals with the slow rolling-up taking place far behind the wing. The mathematical model of the wake is described and examples of the initial roll-up phase have been calculated for three wakes of different thicknesses and elliptic cross-sections, subjected to uniform downwash (corresponding to elliptic spanwise loading).

Posluns, H., editor

"PROCEEDINGS OF THE INTERNATIONAL WAKE VORTEX MEETING, OTTAWA, ONTARIO, 2-4 DECEMBER 1997"

TP 13166, December 1977, Transport Canada, Transport Development Centre, Montreal, Quebec, Canada.

This report is a record of the international meeting on Wake Vortex Prediction, which took place in Ottawa, Ontario, on December 2-4, 1997, and was hosted by Transport Canada. The principal objectives of this meeting were to promote international cooperation in the development of a real-time wake vortex forecasting system and to discuss improved aviation safety and efficiency in relation to

wake vortex modelling, real-time prediction, and meteorological requirements. Experts from Canada, Russia, Belgium, the United States, the United Kingdom, France, and Germany explained their perspectives on the wake vortex issues as well as their proposed solutions. Representatives of airlines, pilots, air navigation service providers, air traffic controllers, airport authorities, governments, and aircraft manufacturers presented their views on the issues.

Pothou, K. P., Voutsinas, S. G., Huberson, S. G. and Knio, O. M.

"APPLICATION OF 3D PARTICLE METHOD TO THE PREDICTION OF AERODYNAMIC SOUND"

ESAIM Proceedings, Vol. 1, 1996, pp. 349-362.

Low-Mach-number aeroacoustic theories are applied to predict far-field sound emission from vortex-dominated flows. The latter are simulated using three-dimensional vortex methods. Both particle schemes and filament-based schemes are used. Comparisons of model predictions with theoretical and experimental results on the interaction of two vortex rings are first discussed. Next, the schemes are used to examine the effect of initial conditions and 3D perturbations on the properties of the far-field acoustic pressure. Finally, a more elaborate wind-turbine model is presented and its application to the evaluation of several turbine-blade designs is summarized.

Potsdam, M. and Pulliam, T.

"TURBULENCE MODELING TREATMENT FOR ROTORCRAFT WAKES"

AHS Aeromechanics Specialist's Meeting, Jan. 2008, San Francisco, CA.

This work investigates the influence of turbulence modeling in the vortical wake of rotorcraft simulations. It is seen that for a range of flight conditions, but especially hover, overall rotor performance prediction can be significantly affected by the wake turbulence model characteristics. The characteristics of some baseline turbulence model formulations (e.g. Baldwin-Barth, Spalart-Allmaras) are observed to produce too much turbulent eddy viscosity if the production is based on the vorticity field of the vortex-dominated rotor wake. Due to the excess production of the turbulent eddy viscosity in the wake, and its subsequent convection and diffusion, the wall-bounded viscous flow is modified. To ameliorate these difficulties, turbulence model modifications in the wake, such as turning off the production source terms, are evaluated. They are shown to improve solution accuracy compared with experimental data for a quarter-scale V-22 isolated rotor in hover, a CH-47 isolated rotor in hover, and a UH-60A in forward flight at high thrust coefficient. The overall effect on rotor performance can be several points in rotor figure of merit or a variation in stall boundary thrust coefficient.

Potts, J. R. and Crowther, W. J.

"VISUALISATION OF THE FLOW OVER A DISC-WING"

9th International Symposium on Flow Visualization, August 2000, Paper 247, Edinburgh, Scotland, UK.

An experimental investigation into the flow characteristics of a disc-wing has been carried out in a low-speed wind tunnel over a flow speed range of 0 to 20 m/s. The disc-wing considered has an axis-symmetric, approximately elliptic cross-section and hollowed out underside cavity. The aim of this research was to gain an understanding of the complex three-dimensional flow structures, to identify regions receptive to flow control technologies such as vortex generators or synthetic (massless) jets. Flow visualization techniques including surface paint and smoke wire methods have been utilized to determine the position and form of surface flow structures.

Pourhashem, H. and Sunil, K.

"BOW SHOCK/VORTEX INTERACTION: EFFECT OF REDUCING THE VORTEX HEIGHT ON STRUCTURE OF THE GENERATED FLOW FIELD"

AIAA Paper 2019-0947, January 2019, San Diego, CA.

The present computational study examines the effect of vortex height on characteristics of bow shock/vortex interaction as a practical technique for improving mixing of fuel and air in Scramjet engines. The bow shock/vortex interaction is induced through placing a vortex generator in the form of a semi-span wing section at an angle of attack upstream of a flat plate with an injection slot. The vortex interacts with the injection induced bow shock, and for a sufficiently strong interaction a supersonic vortex breakdown is expected. The results of the computational study demonstrate that reducing the vortex height leads to the interaction of the vortex with the stronger portion of the bow shock, which results in a vortex breakdown for all examined jet momentum ratios. Results indicate that moving the vortex center close to the plate surface leads to a significant destruction of the vortex core and formation of large subsonic region and a downstream displacement of the primary separation shock due to the Mach number deficit. Additionally, increased mixing of injectant with the supersonic cross flow for all examined cases is observed.

Pourhashem, H., Kalkhoran, I. M. and Sunil, K.

"INTERACTION OF VORTEX WITH BOW SHOCK WAVE: COMPUTATIONAL MODEL, EXPERIMENTAL VALIDATION, ENHANCED MIXING"

AIAA JOURNAL, Vol. 56, No. 8, August 2018, pp. 3071-3085.

A computational model is developed using a delayed detached-eddy simulation to examine the various aspects of shock-wave/vortex interactions, in which the specific case of naturally formed bow shock wave generated during a sonic injection into a supersonic crossflow is considered. The model is validated by comparing with experimental results obtained previously and is deployed to investigate the effects of shock/vortex interaction on mixing characteristics of supersonic flows. A vortex generator, in the form of a semispan wing section, is placed at an angle of attack upstream of an injection location. The resultant vortex interacts with the bow shock, and for a sufficiently strong interaction, there is breakdown of the supersonic vortex. The vortex bursting observed during the computational study is in a very good agreement with a previous physical model. The computational results demonstrate that

the shock/vortex interaction can be an effective method of mixing enhancement because it results in redistribution and increase of vorticity in the flowfield, which enhances the entrainment and eventual mixing of injectant and supersonic crossflow.

Pourhashem, H., Kalkhoran, I. M., Finch, P. and Kumar, S.

"STUDY OF SHOCK WAVE/VORTEX INTERACTION FOR SUPERSONIC MIXING ENHANCEMENT"

AIAA Paper 2017-4648, July 2017, Atlanta, GA.

In the present study, the characteristics of a shock wave/vortex interaction for the enhancement of fuel air mixing in scramjet engines suitable for hypersonic vehicles is investigated. The scheme is based on the previous work developed by Kalkhoran et al. (1998) in the area of shock wave/vortex interaction in which a dramatic supersonic vortex bursting was shown. This study involves positioning a vortex generator, in the form of a semi-span wing section placed at an angle of attack, upstream of an injection slot. The vortex interacts with the naturally formed bow shock due to conventional injection, and for sufficiently strong interaction a supersonic vortex breakdown is expected. Computational investigations are conducted to validate the results of the experimental study using the Reynolds Stress Model (RSM). The results of the present computational investigation are in good agreement with the experimental data, confirming the characteristics of the supersonic vortex breakdown observed during the experimental study. Furthermore, computational results demonstrate the enhanced mixing and shortening of the combustion length for the cases involving the supersonic shock/vortex interaction.

Povitsky, A., Zheng, T. and Vatisstas, G.

"EFFECT OF VORTEX PROFILE ON SOUND GENERATION IN A NON-UNIFORM FLOW"

Lecture Notes in Computer Science, Vol. 2668, 2003, pp. 826-836

The propagation of acoustic waves originating from stretching of intense self-similar vortices in the non-uniform mean flow is studied by numerical modeling using high-order compact approximation. Near-wall stretching of initial vortex by the stagnation flow leads to sound radiation from the generated pressure quadrupole. To mimic unsteady stagnation flows and impingement jets, the stagnation flow has been switched off at some time moment. Subsonic stagnation flow and flow around a cylinder are taken as prototypes of real-world flows with strong gradients of mean pressure and velocity. Compressibility of the background mean flow and the vortex are considered and its effect on amplification of acoustic pressure is discussed. Generation of sound by stretching of vorticity dipole leads to formation of a three-spot wave with maximum acoustic pressure at the centerline. Since aeroacoustic applications require good physical approximations for the viscous nature of tip vortices, several semi-empirical profiles of vortex velocity were considered. The intensity and directivity of acoustic wave patterns appear to be quite different for Taylor and Vatisstas vortices.

Powell, A.

"THEORY OF VORTEX SOUND"

Journal Acoustical Society of America, Vol. 36, No. 1, January 1964, pp. 177-195

Physical arguments are followed by mathematical developments to show how aerodynamic sound is generated as a result of the movement of vortices, or of vorticity, in an unsteady fluid flow. Changes in circulation or area of a vortex ring give rise to a dipole sound field, the former being illustrated by oscillating flow about a fixed sphere, and the latter by a simple model for the aeolian tone attributable to the stretching of vortex rings. Because in a free flow there can be no change of the total vortex strength (circulation times area), there is no net dipole strength, but each moving element of vorticity still causes a local dipole like flow; each element of moving vorticity acts with some equal and opposite movement elsewhere in the flow so that together they form an oblique quadrupole, although the total effect must be reducible to an assembly of lateral quadrupoles. A cardinal result is that the vorticity in a slightly compressible fluid can be considered to induce the whole flow field, both the hydrodynamic part and the acoustic part. With vorticity taken as the common basis, a slightly compressible flow is compared to the corresponding incompressible one, which may be used in the evaluation of the sound-radiation formula. The theory is particularly well-structured to estimate sound from flows described in terms of vorticity: the sound field is determined for two rectilinear vortices spinning about an axis between them, and its basis for similarity methods is demonstrated in application to free shear flow and jet flow.

Powell, A.

"A BASICALLY MONOPOLE SOURCE FORMULATION FOR VORTEX-GENERATED SOUND"

J. Acoustical Society of America, Vol. 97, No. 4, April 1995, pp. 2144-2146.

Lighthill's source term for aerodynamic sound generation can be expressed in terms of the squares of the vorticity and of the principal rates of strain of the sound-generating fluid, in the usual incompressible approximation. These represent local monopole source regions. When there are discrete interacting vortices, the former has the physical interpretation of the sound emission being associated with the occurrence of pressure minima at vortex cores, while the latter may be imagined to be the emission associated with the pressure maxima in regions between colliding vortices. The quadrupole source volume integrals converge rapidly, so the whole source region may be thought of as compact, the poor convergence difficulties associated with the use of the 'incompressible' pressure of previous 'simple source' or 'dilatational' theories being avoided.

Powell, A.

"VORTEX SOUND THEORY: DIRECT PROOF OF EQUIVALENCE OF 'VORTEX FORCE' AND 'VORTICITY-ALONE' FORMULATIONS"

Journal of Acoustical Society of America, Vol. 97, No. 3, March 1995, pp. 1534-1537.

In the theory of vortex sound the far-field compact source strengths are the volume integrals of the time differential of the vortex force. Mohring's method, using a vector Green's function, produces instead the vorticity-alone volume integrals that do not explicitly involve the velocity of the inviscid incompressible sound-generating flow. Direct proofs that these different integral results are in fact exactly equal are offered: given one form, the other can be found with no appeal to acoustical theory whatsoever. The implications of these integral formulations is discussed.

Powell, A.

"WHY DO VORTICES GENERATE SOUND?"

Transactions of the ASME, Vol. 117, June 1995, pp. 252-260

Emphasizing physical pictures with a minimum of analysis, an introductory account is presented as to how vortices generate sound. Based on the observation that a vortex ring induces the same hydrodynamic (incompressible) flow as does a dipole sheet of the same shape, simple physical arguments for sound generation by vorticity are presented, first in terms of moving vortex rings of fixed strength and then of fixed rings of variable strength. These lead to the formal results of the theory of vortex sound, with the source expressed in terms of the vortex force, and of the form introduced by Moehring in terms of vortex moment. The simple 'Contiguous Method' of finding the contiguous acoustic field surrounding an acoustically compact hydrodynamic (incompressible) field is also discussed. Some very simple vortex flows illustrate the various ideas. These are all for acoustically compact, low Mach number flows of an inviscid fluid, except that a simple argument for the effect of viscous dissipation is given and its relevance to the 'dilatation' of a vortex is mentioned.

Powell, A.

"VORTEX SOUND: AN ALTERNATIVE DERIVATION OF MOHRINGS FORMULATION"

Journal Acoustical Society of America., Vol. 97, Issue 1, Jan. 1995, pp. 684-686

By considering that the radial flow velocity at a spherical bounding surface due to a system of vortex rings (as given by the so-called Biot-Savart analogy for incompressible flow), fixed but of variable strength, drives the contiguous acoustic fields, simple physical arguments are presented that yield the results for dipole and quadrupole vortex sound in Mohring's form.

Powell, J. D., Jennings, C. and Holforthy, W.

"USE OF ADS-B AND PERSPECTIVE DISPLAYS TO ENHANCE AIRPORT CAPACITY"

24th Digital Avionics Systems Conference, Vol. 1, Nov. 2005, pp. 4.D.4-1--4.D.4-9

As the growth in air travel continues over the coming decades, there will need to be increases in the capacity of the airspace system, especially airports. Technology associated with GPS, along with changes in procedures between air traffic controllers and pilots, has the capability to provide much of

the required growth without sacrificing safety and without requiring wholesale expansions of airport land areas. The use of GPS to augment radar surveillance through Automatic Dependent Surveillance - Broadcast (ADS-B) provides a substantial improvement in surveillance accuracy and provides every pilot with information on neighboring traffic, information that does not exist now. Wake vortex turbulence of neighboring traffic is one of the limiting factors on parallel runway spacing and the in-trail spacing of aircraft. This paper shows how the impact of wake turbulence can be substantially reduced by the use of ADS-B and appropriate displays. The paper presents results of analyses, pilot simulations, and flight-testing that show the required runway spacing can be reduced from the current 4300 ft. to 750 ft., thus substantially improving landing capacity while minimizing cost and the effect on the environment.

Prasad, N. S.

"RECENT ADVANCES IN WIND LIDAR TECHNOLOGIES FOR CHARACTERIZATION OF WAKE VORTICES"

AIAA Paper 2018-2863, June 2018, Atlanta, GA.

Fast-time wake vortex models have been studied in various details for possible operational and research applications related to air traffic management. The wake vortex Light Detection and Ranging (lidar) technology plays a critical role in validating these numerical wake models. With the advent of lasers, various types of remote sensing techniques and systems began to develop in laboratories across the world. Fundamentally, all these techniques depend upon sensing of wind velocities at a given range coupled with effective algorithms for extraction of wake vortex characteristics. When solid-state lasers appeared on the scene, practical lidar systems were built for field operations. These lidars have enabled wake vortex data collection in airports under various environmental and air craft orientation conditions for analysis and validation of CFD generated fast-time wake vortex models. In this paper, a brief history of wake vortex measurements followed by prominent field campaigns conducted by NASA Langley Research Center will be discussed. In subsequent sections, salient aspects of recently developed novel wind lidar technology will be presented.

Prasad, N. S., Sibell, R., Vettori, S., Higgins, R. and Tracy, A.

"AN ALL-FIBER, MODULAR, COMPACT WIND LIDAR FOR WIND SENSING AND WAKE VORTEX APPLICATIONS"

Proceedings SPIE 9465, Laser Radar Technology and Applications XX, April 2015, Baltimore, MD. Next-Generation Spectroscopic Technologies VIII, June 2015.

This paper discusses an innovative, compact and eye safe coherent lidar system developed for wind and wake vortex sensing applications. With an innovative all-fiber and modular transceiver architecture, the wind lidar system has reduced size, weight, and power requirements, and provides enhanced performance along with operational elegance. This all-fiber architecture is developed around fiber seed laser coupled to uniquely configured fiber amplifier modules. The innovative features of this lidar system, besides its all-fiber architecture, include pulse width agility and user programmable 3D hemispherical scanner unit. Operating at a wavelength of 1.5457 microns and with a

PRF of up to 20 KHz, the lidar transmitter system is designed as a Class I system with dimensions of 30' (W) x 46' (L) x 60' (H). With an operational range exceeding 10 km, the wind lidar is configured to measure wind velocities of greater than 120 m/s with an accuracy of ± 0.2 m/s and allow range resolution of less than 15 m. The dynamical configuration capability of transmitted pulse widths from 50 ns to 400 ns allows high resolution wake vortex measurements. The scanner uses innovative liquid metal slip ring and is built using 3D printer technology with light weight nylon. As such, it provides continuous 360-degree azimuth and 180-degree elevation scan angles with an incremental motion of 0.001 degree. The lidar system is air cooled and requires 110 V for its operation. This compact and modular lidar system is anticipated to provide mobility, reliability, and ease of field deployment for wind and wake vortex measurements. Currently, this wind lidar is undergoing validation tests under various atmospheric conditions. Preliminary results of these field measurements of wind characteristics that were recently carried out in Colorado are discussed.

Prasad, N. S., Tracy, A., Vettori, S., Higgins, R. and Sibell, R.

"INNOVATIVE FIBER-LASER ARCHITECTURE BASED COMPACT WIND LIDAR"

18th Coherent Laser Radar Conference, June 2016, Boulder, CO.

This paper describes an innovative, all-fiber, compact, and eyesafe coherent lidar system developed for wind and wake vortex sensing applications. The all-fiber lidar, with modular architecture, incorporates an integrated 3D scanner that provides user programmable, continuous 360-degree azimuth and 180-degree elevation scan angles. Operating at 1.54 microns, the lidar allows pulse width agility from 50 - 400 ns with a variable PRF of up to 20 KHz. The wind lidar is air cooled with overall dimensions of 30 cm x 46 cm x 60 cm and is designed as a Class I system. This lidar is capable of measuring wind velocities greater than 120 ± 0.2 m/s over ranges greater than 10 km and with a range resolution of less than 15 m. In this paper, the key features of lidar instrumentation and its functionality are discussed followed by results of recent wind forecast measurements on a wind farm.

Premaratne, P. and Hu, H.

"A NOVEL VORTEX METHOD TO INVESTIGATE WIND TUNNEL NEAR-WAKE CHARACTERISTICS"

AIAA Paper 2017-4213, June 2017, Denver, CO.

We utilize vortex methods to identify possible mechanisms which cause vortex filaments to break-up in the wake behind a horizontal axis wind turbine (HAWT). This study was inspired by the flow characteristics observed in PIV measurements from an experiment conducted at the Atmospheric Boundary Layer (ABL) tunnel at ISU using a scaled model of an industry standard HAWT. Measurements revealed the presence of a tip vortex filament and a secondary vortex filament emanating from the mid-span location of the blade. The mid-span vortex has twice the circulation of the tip vortex filament and the vortices break-up at $X/D=0.5$ axial station. Both filaments showed expansion with the wake and a merging effect between the filaments. Our investigation using a vortex-blob based method (2D)

and a filament-based method (3D) captured wake expansion of both filaments as well as the converging behavior, which could result in wake instability.

Premaratne, P. and Hu, H.

"ANALYSIS OF TURBINE WAKE CHARACTERISTICS USING DYNAMIC MODE DECOMPOSITION"

AIAA Paper 2017-4214, June 2017, Denver, CO.

We examine the flow characteristics behind a three-bladed horizontal-axis wind turbine via experiments in a large-scale wind tunnel with a scaled model placed in a typical Atmospheric Boundary Layer (ABL) wind under neutral stability conditions. A high-resolution digital particle image velocimetry (PIV) system was used to study the detailed flow field. Besides analyzing average statistics of the flow quantities such as mean velocity and vorticity distributions in the wake, 'phase-locked' PIV measurements also elucidated further details of the vortex structures in the wake for a frozen position of the blades. Phase-averaged measurements of the near-wake ($0 < X/D < 1.0$) were arranged to resemble a time resolved snapshot series to be analyzed by Dynamic Mode Decomposition (DMD) method, an advanced statistical method capable of detecting dominant spatial and temporal structures buried in a flow field. The DMD method managed to identify the high energy modes that dominate in a series of given regions of interest that encompasses the shear layer. The DMD modes revealed a transition in modal shape from axisymmetric to asymmetric as the vortical structures travel downstream and break-up at a critical $X/D = 0.5$. Axisymmetric mode produced in the DMD analysis agreed satisfactorily with a low order reconstruction obtained from a prior POD analysis. A full field DMD analysis of the shear layer region yielded a spatially and temporally decaying mode which encapsulates both asymmetric and axisymmetric modes observed previously.

Priess, S. and Weitz, L. A.

"ASSIGNED SPACING GOAL CALCULATION FOR INTERVAL MANAGEMENT PAIRED APPROACH OPERATIONS"

Report MTR190104, December 2018, Mitre Corporation, McLean, VA.

This is a MITRE report entitled 'Assigned Spacing Goal Calculation for Interval Management Paired Approach Operations.'

Priest, A. J., Dobney, D. G. and Hill, R. P.

"MEASUREMENTS IN THE NEAR-WAKE OF A TRANSPORT MODEL TO DETERMINE THE LIFT, DRAG AND DRAG COMPONENTS USING MASKELL'S ANALYSIS"

RAE TR-81012, February 1981, Royal Aircraft Establishment, Farnborough, England.

Extensive measurements have been made on a plane normal to the wake of a swept-wing/fuselage model of airbus type, at $C_{sub-L} = 0.49$ in incompressible flow, using a computer-controlled wake-traverse system incorporating a null-reading five-hole yawmeter probe. The results define the detailed distributions of total pressure defect, flow velocity, flow angles and streamwise vorticity in the viscous wake at that plane. The results have been analyzed within the basic theoretical framework set out by Maskell (1973), allowing the calculation of lift and drag from traverse data, and the resolution of the drag into provisionally-defined components $C_{sub-D sub I}$ and $C_{sub-D sub II}$, respectively relating to the profile drag and vortex drag.

Primeggia, C. and Hodgkins, P. D.

"DEPARTURE EXCLUSION ZONE (DEZ) - A FUTURE CONCEPT TO ENHANCE RUNWAY OPERATIONS USING AIRCRAFT DERIVED DATA"

Fifth NASA Integrated Communications, Navigation, and Surveillance (ICNS) Conference and Workshop, May 2005, Fairfax, VA

This paper highlights a concept for a Departure Exclusion Zone (DEZ) tool. Wake turbulence accidents and incidents have been, and continue to be, a significant contributor to the worldwide safety statistics. The safety concern of wake vortices, particularly when lighter aircraft are following heavy aircrafts, has caused the FAA to enact minimum separation requirements during the arrival and departure phases of flight. The wake-turbulence separation criteria, while necessary, are currently a limiting factor in several airport capacities. This paper examines the technical requirements for a system that relieves the departure constraints enhancing the efficiency of runway operations. The proposed system uses the Flight Management System/autopilot to establish tracks that avoid the wake of the preceding aircraft. Given that an aircraft can provide meteorological (wind, temperature, and air density) and state data (model, speed, weight, etc.), the wake vortices can be calculated with sufficient accuracy to develop individual departure routes (tracks) for each aircraft to avoid the wake of the preceding aircraft. The proposed DEZ system acquires the aircraft data, calculates the exclusion zone for each aircraft and provides the results to the controller's display and to the cockpit.

Pritchett, A. R.

"PILOT PERFORMANCE AT COLLISION AVOIDANCE DURING CLOSELY SPACED PARALLEL APPROACHES"

Air Traffic Control Quarterly, Vol. 7, No. 1, 1999, pp. 47-75.

To examine the issues with collision avoidance during closely spaced parallel approaches, two related studies have been performed. First, the most hazardous relative positions of aircraft on parallel approaches were identified through fast-time simulations of collision trajectories. Second, a part-task flight simulator evaluation of traffic displays, the need for automatic alerts and for autopilot control of the approach was conducted. While a need was identified for alerting systems to command effective avoidance maneuvers, pilots were found to frequently not conform to the commanded avoidance

maneuver, with a resulting decrease in performance. Based on these results, concerns meriting further study are discussed..

Privett, R., Collier, G., Eustace, P. and Grant, A. L.

"WAKE VORTEX REPORTING SCHEME AND METEOROLOGICAL DATA COLLECTION SYSTEM"

VII/53563/95, October 1995, European Commission, Brussels, Belgium

A feasibility study for implementing Wake Vortex Reporting Systems (WVRS) and meteorological monitoring systems at seven European airports (Paris Orly, Frankfurt, Brussels, London Heathrow, Gatwick, Amsterdam, and Milan) was completed. The intent is to gather a comprehensive range of data on wake vortex incidents and amass data on airport meteorological and wind conditions through a wake vortex reporting scheme and meteorological data capture system at the European airports. The data would be used to validate models and to improve short term windspeed and direction forecasts for use in Wake Vortex Advisory Schemes.

Probst, S., Knopp, T., Francois, D. G. and Grabe, C.

"SCALE-RESOLVING SIMULATIONS OF THE STREAMWISE VORTEX DOWNSTREAM OF A DELTA WING"

AIAA Paper 2019-0331, January 2019, San Diego, CA.

This paper investigates simulation strategies to accurately predict the streamwise evolution of the longitudinal vortex that is generated at the leading edge of a delta wing. For this purpose, different hybrid RANS/LES approaches are assessed by comparison with experimental reference data. As test case a new wind tunnel experiment is considered, which provides detailed data of the vortex evolution downstream of the delta-wing trailing edge using stereoscopic particle image velocimetry. Since in this work the vortex development in the wake is of primary interest, the flow around the delta wing is modeled with RANS, whereas a scale-resolving LES is only applied in its wake. This approach reduces the computational effort compared to pure LES and enables a systematic study of different grid designs and suitable positions of the RANS/LES interface. The results show the importance of applying synthetic turbulence to trigger the generation of resolved structures at the RANS/LES interface.

Proctor, F. and Hamilton, D. W.

"WAKE VORTEX TRANSPORT AND DECAY FROM THE PERSPECTIVE OF PARALLEL RUNWAYS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001.

For aircraft approaching/departing a single runway, safe aircraft separations may be determined from the time interval needed for a wake vortex to either dissipate or transport out of the flight corridor. For parallel runways, predictions for safe conditions are more complex since crosswinds can transport wake vortices into adjacent flight corridors. During instrument meteorological conditions (IMC), capacity is

decreased for airports with parallel runways, since operations may be reduced or shut down along one of the runways due to the uncertain position of the laterally-drifting wakes. Potential encounters with wake vortices generated from adjacent corridors can be avoided by ensuring that runways are built with adequate lateral separation. However, since this is not always feasible and many parallel runways are in place, capacity improvements must benefit from predictions of wake vortex position and lifetime. Important environmental parameters for predicting wake vortex transport and demise for parallel runway systems are the vertical profile of ambient crosswind and intensity of ambient turbulence. A system designed to predict vortex spacing for parallel runways, at minimum, should be able to predict if wake vortices from adjacent runways can reach the flight corridor before vortex demise. This will require an understanding of how vortices interact with the ground, crosswind shear, and ambient turbulence. We are investigating these interactions with the LES Terminal Area Simulation System (TASS) and will present results at the conference. Our results show that for optimal conditions of strong crosswinds and weak ambient turbulence, wake vortices may drift laterally up to distances of 27 effective spans for out of ground effect and 17 effective spans for in ground effect.

Proctor, F. H.

"NUMERICAL STUDY OF A LONG-LIVED, ISOLATED WAKE VORTEX IN GROUND EFFECT"

AIAA Paper 2014-2469, June 2014, Atlanta, GA.

This paper examines a case observed during the 1990 Idaho Falls Test program, in which a wake vortex having an unusually long lifetime was observed while in ground effect. A numerical simulation is performed with a Large Eddy Simulation model to understand the response of the environment in affecting this event. In the simulation, it was found that one of the vortices decayed quickly, whereas the remaining vortex persisted beyond typical vortex lifetimes found in ground effect. This unusual behavior was found to be related to the first and second vertical derivatives of the ambient crosswind.

Proctor, F. H.

"TWO DIMENSIONAL PARAMETRIC STUDIES OF WAKE VORTEX INTERACTION WITH THE ATMOSPHERE"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 93-108.

Results from parametric runs using two-dimensional TASS are presented. First, a set of experiments are presented that examine the sensitivity of the aircraft initiation height for an 'in ground effect' case with weak crosswind. Interaction between the ground and the wake vortex produces an oscillatory rebound whose phase and amplitude are a function of the generation height. A second set of experiments are presented which examine the influence on crosswind shear. Shear layers, such as may be found between the nocturnal stable layer and the residual layer, can act to deflect vortices upward. Further investigation reveals that the second derivative of the crosswind can differentially reduce the descent speed of each member of a vortex pair, causing tilting of the vortex pair. If sufficiently large, the second derivative of crosswind can deflect the vortex pair upwards, with the sign of the second

derivative determining which of the two vortices rises to a higher altitude. Linear shear, on the other hand, caused no change in the descent speed of the vortices; thus having no effect on the orientation of the vortices. Observed and model data from an actual case are presented in support of the conclusion regarding the influence of shear on rising vortices.

Proctor, F. H.

"NASA LANGLEY'S NUMERICAL MODELLING EFFORT TO UNDERSTAND THE INTERACTION OF AIRCRAFT WAKE VORTICES WITH THEIR ENVIRONMENT"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 63-64.

Numerical modelling of aircraft wake vortices and the turbulent atmospheric boundary layer are being used at NASA Langley to help understand and quantify wake vortex transport and decay. A large-eddy simulation model which includes a meteorological framework is applied to study the interaction of wake vortices with environments characterized by crosswind shear, stratification, humidity, and atmospheric turbulence. Results from the numerical simulations, along with field measurements are being used to assist in the development of algorithms for an operational wake-vortex aircraft spacing system. The 2-D model is found to be generally valid for studying wake vortex transport (both out of and in ground effect), while the 3-D approach is necessary for realistic treatment of decay. The numerical results with confirming lidar data observed during the Memphis airport field deployments, show that wake vortices decay from the outside with very minimal expansion of the core. Also presented will be 2-D results that show that transport of wake vortices are unaffected when imbedded in uniform rain or fog, but their transport can be strongly affected by the vertical change in ambient crosswind shear. The latter can reduce the rate of vortex descent and in some cases may cause one of the members of the vortex pair to rise.

Proctor, F. H.

"THE NASA-LANGLEY WAKE VORTEX MODELLING EFFORT IN SUPPORT OF AN OPERATIONAL AIRCRAFT SPACING SYSTEM"

AIAA Paper No. 1998-0589, Reno, NV, January 1998

Two numerical modelling efforts, one using a large eddy simulation model and the other a numerical weather prediction model, are underway in support of NASA's Terminal Area Productivity program. The large-eddy simulation model (LES) has a meteorological framework and permits the interaction of wake vortices with environments characterized by crosswind shear, stratification, humidity, and atmospheric turbulence. Results from numerical simulations are being used to assist in the development of algorithms for an operational wake-vortex aircraft spacing system. A mesoscale weather forecast model is being adapted for providing operational forecast of winds, temperature, and turbulence parameters to be used in the terminal area. The 2-D model is found to be generally valid for studying wake vortex transport, while the 3-D approach is necessary for realistic treatment of decay via

interaction of wake vortices and atmospheric boundary layer turbulence. Presented are results showing that wake vortex transport is unaffected by uniform fog or rain, but wake vortex transport can be strongly affected by nonlinear vertical change in the ambient crosswind. Both simulation and observations show that atmospheric vortices decay from the outside with minimal expansion of the core. Vortex decay and the onset of three-dimensional instabilities are found to be enhanced by the presence of ambient turbulence.

Proctor, F. H.

"NASA LANGLEY'S NUMERICAL MODELLING EFFORT TO UNDERSTAND THE INTERACTION OF AIRCRAFT WAKE VORTICES WITH THEIR ENVIRONMENT"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

Numerical modelling of aircraft wake vortices and the turbulent atmospheric boundary layer are being used at NASA Langley to help understand and quantify wake vortex transport and decay. A Large-Eddy simulation model which includes a meteorological framework is applied to study the interaction of wake vortices with environments characterized by crosswind shear, stratification, humidity, and atmospheric turbulence. Results from the numerical simulations, along with field measurements are being used to assist in the development of algorithms for an operational wake-vortex aircraft spacing system. Described are the goals and modelling approach, as well as achievements obtained to date. Simulation results and comparisons with field data will be presented. The numerical results with confirming lidar data observed during the Memphis airport field deployments, show that wake vortices decay from the outside with very minimal expansion of the core. This contrasts with previous numerical modelling studies which have reported either the wake vortex decays from the inside with a significant expansion of the core, or very little decay occurs until sinusoidal instabilities take place.

Proctor, F. H.

"NUMERICAL SIMULATION OF WAKE VORTICES MEASURED DURING THE IDAHO FALLS AND MEMPHIS FIELD PROGRAMS"

AIAA Paper No. 1996-2496, New Orleans, LA, June 1996

A numerical large-eddy simulation model is under modification and testing for application to aircraft wake vortices. The model, having a meteorological framework, permits the interaction of wake vortices with environments characterized by crosswind shear, stratification, and humidity. As part of the validation process, model results are compared with measured field data from the 1990 Idaho Falls and the 1994-1995 Memphis field experiments. Cases are selected that represent different aircraft and a cross section of meteorological environments. Also included is one case with wake vortex generation in ground effect. The model simulations are initialized with the appropriate meteorological conditions and a post roll-up vortex system. No ambient turbulence is assumed in our initial set of experiments, although turbulence can be self-generated by the interaction of the model wakes with the ground and environment.

Proctor, F. H.

"THE LARC WAKE VORTEX MODELLING EFFORT"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 75-92

The purpose of the modelling effort at NASA Langley, including goals, is outlined in this presentation. Included is a description of the numerical model that is used for the NASA wake vortex modelling effort and the approach that is taken to achieve the stated goals. Also shown are: 1) a demonstration of using the model in a fog environment; 2) preliminary results from a 3-D simulation in a nonturbulent and thermally-stable environment with comparison to a comparable 2-D simulation of the same event; and 3) several validation cases from the Idaho-Falls and Memphis field studies where results from the 2-D version of the model are compared with Lidar and tower data.

Proctor, F. H.

"INTERACTION OF AIRCRAFT WAKES FROM LATERALLY SPACED AIRCRAFT"

AIAA Paper 2009-0343, Jan. 2009, Orlando, FL

Large Eddy Simulations are used to examine wake interactions from aircraft on closely spaced parallel paths. Two sets of experiments are conducted, with the first set for in ground effect (IGE). The initial wake field for each aircraft represents a rolled-up vortex pair generated by a B-747. Parametric sets include wake interactions from aircraft pairs with lateral separations of 400, 500, 600, and 750 ft. The simulation of a wake from a single aircraft is used as baseline. The study shows that the wake vortices from either a pair or a formation of B-747's that fly with very close lateral spacing, last longer than those from an isolated B-747. For OGE, the inner vortices between the pair of aircraft, ascend, link and quickly dissipate, leaving the outer vortices to decay and descend slowly. For the IGE scenario, the inner vortices ascend and last longer, while the outer vortices decay from ground interaction at a rate similar to that expected from an isolated aircraft. Both OGE and IGE scenarios produce longer-lasting wakes for aircraft with separations less than 600 ft. The results are significant because concepts to increase airport capacity have been proposed that assume either aircraft formations and/or aircraft pairs landing on very closely spaced runways.

Proctor, F. H. and Ahmad, N. N.

"CROSSWIND SHEAR GRADIENT AFFECT ON WAKE VORTICES"

AIAA Paper No. 2011-3038, June 2011, Honolulu, Hawaii.

Parametric simulations with a Large Eddy Simulation (LES) model are used to explore the influence of crosswind shear on aircraft wake vortices. Previous studies based on field measurements, laboratory experiments, as well as LES, have shown that the vertical gradient of crosswind shear, i.e. the second

vertical derivative of the environmental crosswind, can influence wake vortex transport. The presence of nonlinear vertical shear of the crosswind velocity can reduce the descent rate, causing a wake vortex pair to tilt and change in its lateral separation. The LES parametric studies confirm that the vertical gradient of crosswind shear does influence vortex trajectories. The parametric results also show that vortex decay from the effects of shear is complex since the crosswind shear, along with the vertical gradient of crosswind shear, can affect whether the lateral separation between wake vortices is increased or decreased. If the separation is decreased, the vortex linking time is decreased, and a more rapid decay of wake vortex circulation occurs. If the separation is increased, the time to link is increased, and at least one of the vortices of the vortex pair may have a longer life time than in the case without shear. In some cases, the wake vortices may never link.

Proctor, F. H. and Hamilton, D. W.

"EVALUATION OF FAST-TIME WAKE VORTEX PREDICTION MODELS"

AIAA Paper 2009-0344, Jan. 2009, Orlando, FL

Current fast-time wake models are reviewed and three basic types are defined. Predictions from several of the fast-time models are compared. Previous statistical evaluations of the APA-Sarpkaya and D2P fast-time models are discussed. Root Mean Square errors between fast-time model predictions and Lidar wake measurements are examined for a 24 hr period at Denver International Airport. Shortcomings in current methodology for evaluating wake errors are also discussed.

Proctor, F. H. and Han, J.

"NUMERICAL STUDY OF WAKE VORTEX INTERACTION WITH THE GROUND USING THE TERMINAL AREA SIMULATION SYSTEM"

AIAA Paper No. 1999-0754, Reno, NV, January 1999

A sensitivity study for the 'in-ground effect' on aircraft wake vortices has been conducted using a validated large eddy simulation model. The numerical results are compared with observed data and show good agreement for vortex decay and lateral transport. The vortex decay rate is strongly influenced by the ground, but appears somewhat insensitive to ambient turbulence. In addition, the results show that the ground can affect the trajectory and descent-rate of a wake-vortex pair at elevations up to about $3B$ (where B is the initial vortex separation). However, the ground does not influence the average circulation of the vortices until the cores descend to within about $0.6B$ after which time the ground greatly enhances their rate of demise. Vortex rebound occurs in the simulations, but is more subtle than shown in previous numerical studies.

Proctor, F. H. and Switzer, G. F.

"NUMERICAL SIMULATION OF AIRCRAFT TRAILING VORTICES"

9th Conf. On Aviation, Range and Aerospace Meteorology, Paper 7.12, AMS, Orlando, FL, September 2000.

The National Aeronautics and Space Administration (NASA) under its Terminal Area Productivity program is investigating new technologies that will allow increased airport capacity while maintaining the present standards for safety. As an element of this program, the Aircraft Vortex Spacing System is being demonstrated in July 2000 at Dallas Ft.-Worth Airport. This system allows reduced aircraft separations, thus increasing the arrival and departure rates, while ensuring that wake vortices do not endanger trailing aircraft. The system uses predictions of wake vortex position and strength based on input from the current weather state. This prediction is accomplished by a semi-empirical model developed from theory, field observations, and relationships derived from numerical wake vortex simulations. Numerical experiments with a Large Eddy Simulation (LES) model are being conducted to provide guidance for the enhancement of these prediction algorithms. This paper summarizes many of the previous investigations with the model and presents some new results regarding the onset of wake vortex decay.

Proctor, F. H., Ahmad, N. N., Switzer, G. S. and Duparcmeur, F. M. L.

"THREE-PHASED WAKE VORTEX DECAY"

AIAA Paper No. 2010-7991, Toronto, Canada, August 2010.

A detailed parametric study is conducted that examines vortex decay within turbulent and stratified atmospheres. The study uses a large eddy simulation model to simulate the out-of-ground effect behavior of wake vortices due to their interaction with atmospheric turbulence and thermal stratification. This paper presents results from a parametric investigation and suggests improvements for existing fast-time wake prediction models. This paper also describes a three-phased decay for wake vortices. The third phase is characterized by a relatively slow rate of circulation decay. and is associated with the ring-vortex stage that occurs following vortex linking. The three-phased decay is most prevalent for wakes imbedded within environments having low-turbulence and near-neutral stratification.

Proctor, F. H., Hamilton, D. W. and Han, J.

"WAKE VORTEX TRANSPORT AND DECAY IN GROUND EFFECT: VORTEX LINKING WITH THE GROUND"

AIAA Paper No. 2000-0757, Reno, NV, January 2000

Numerical simulations are carried out with a three-dimensional Large-Eddy Simulation (LES) model to explore the sensitivity of vortex decay and transport in ground effect (IGE). The vortex decay rates are found to be strongly enhanced following maximum descent into ground effect. The nondimensional decay rate is found to be insensitive to the initial values of circulation, height, and vortex separation. The information gained from these simulations is used to construct a simple decay relationship. This relationship compares well with observed data from an IGE case study. Similarly, a relationship for lateral drift due to ground effect is constructed from the LES data. In the second part of this paper,

vortex linking with the ground is investigated. Our numerical simulations of wake vortices for IGE show that a vortex may link with its image beneath the ground, if the intensity of the ambient turbulence is moderate to high. This linking with the ground (which is observed in real cases) gives the appearance of a vortex tube that bends to become vertically oriented and which terminates at the ground. From the simulations conducted, the linking time for IGE appears to be similar to the linking time for vortices in the free atmosphere; i.e., a function of ambient turbulence intensity.

Proctor, F. H., Hamilton, D. W. and Switzer, G. F.

"TASS DRIVEN ALGORITHMS FOR WAKE PREDICTION"

AIAA Paper No. 2006-1073, Reno, NV, January 2006

The TASS Driven Algorithms for Wake Prediction (TDAWP) is a simple set of algorithms engineered from results of three-dimensional large eddy simulations of wake vortices. The model consists of two equations, one for the prediction of vortex transport and a second for wake vortex decay. The model is designed for real-time predictions of wake vortex position and strength, and is dependent upon, weather conditions. A detailed description of TDAWP, including validation with field data, is included.

Proctor, F. H., Hamilton, D. W., Han, J., and Switzer, G. F.

"SIMULATIONS OF WAKE VORTEX DECAY IN THE ATMOSPHERE"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

As part of a NASA program to increase airport capacity, a numerical large-eddy simulation model has been used to investigate wake vortex behavior in the atmosphere. The primary objective of the numerical studies has been to quantify vortex transport and decay in relation to atmospheric variables. The studies have shown that the rate of vortex decay increases with increasing levels of ambient turbulence (as quantified by the eddy dissipation rate). However, near the ground, the decay rate is independent of the ambient turbulence level. Here, vortex decay is dominated by frictional interaction with the ground. Results also show that the time of vortex linking was primarily influenced by ambient turbulence. This was true even for cases of vortex linking with the ground. Vortex descent was found to be influenced by crosswind shear, large atmospheric eddies, and stratification. Results show that unexpected stalls during vortex descent can be attributed to either crosswind shear or vertical transport due to large planetary boundary layer eddies. Our studies, which assume high-Reynolds number flow with resolved turbulence, have reached different conclusions than those published using laminar models. For example, in cases of the free atmosphere with no crosswind, we find that 1) vortex separation is nearly constant, 2) vortex cores remain tight as the vortex decays, 3) the time of vortex linking is independent of the level of stratification, and 4) wake vortices dissipate once their descent is stalled due to stable stratification.

Proctor, F. H., Hamilton, D. W., Rutishauser, D. K. and Switzer, G. F.

"METEOROLOGY AND WAKE VORTEX INFLUENCE ON AMERICAN AIRLINES FL-587 ACCIDENT"

NASA-TM-2004-213018, January 2004, NASA, Hampton, VA

The atmospheric environment surrounding the crash of American Airlines Flight 587 is investigated. Examined are evidence for any unusual atmospheric conditions and the potential for encounters with aircraft wake vortices. Computer simulations are carried out with two different vortex prediction models and a Large Eddy Simulation model. Wind models are proposed for studying aircraft and pilot response to the wake vortex encounter.

Proctor, F. H., Hinton, D. A., Han, J., Schowalter, D. G. and Lin, Y.-L.

"TWO DIMENSIONAL WAKE VORTEX SIMULATIONS IN THE ATMOSPHERE: PRELIMINARY SENSITIVITY STUDIES"

AIAA Paper No. 1997-0056, Reno, NV, January 1997

A numerical large-eddy simulation model is currently being used to quantify aircraft wake vortex behavior with meteorological observables. The model, having a meteorological framework, permits the interaction of wake vortices with environments characterized by crosswind shear, stratification, and humidity. The addition of grid-scale turbulence as an initial condition appeared to have little consequence. Results show that conventional nondimensionalizations work very well for vortex pairs embedded in stably stratified flows. However, this result is based on simple environments with constant Brunt-Vaisala frequency. Results presented here also show that crosswind profiles exert important and complex interactions on the trajectories of wake vortices. Nonlinear crosswind profiles tended to arrest the descent of wake vortex pairs. The member of the vortex pair with vorticity of same sign as the vertical change in the ambient along-track vorticity may be deflected upwards.

Proctor, P.

"FAA EYES WINGLETS TO CUT WAKE UPSETS"

Aviation Week & Space Technology, Vol. 150, No. 12, 22 March 1999, p. 41

Blended and 'spiroid' winglet designs for commercial aircraft wingtips reduce wingtip vortices, thereby reducing drag. The associated reduction in aircraft wake turbulence during takeoffs and landings will enhance safety and allow a maximization of airspace system capacity by reducing approach and departure intervals between aircraft.

Proot, M. M. J., Sforza, P. M., Wang, F. Y. and Charbonnier, J-M.

"NEAR-FIELD VORTEX-WAKE/PLUME INTERACTION AT LOW SPEED"

Proceedings of FEDSM 98, 1998 ASME Fluids Engineering Division Summer Meeting, FEDSM98-4991, June 1998, Washington, DC.

A combined experimental and analytical study of nearfield vortex-wake/plume interaction in a subsonic flow has been initiated and preliminary results are presented. An engineering model is developed to examine the sensitivity of the various parameters leading to the onset of interaction. The utility of the model is illustrated and the associated strengths, envisioned limitations and possible refinements are discussed. Finally, comparisons are made with flow visualization experiments and good qualitative agreement has been found.

Prosser, C. P. and Wiler, C. D.

"RPV FLYING QUALITIES DESIGN CRITERIA"

AFFDL-TR-76-125, December 1976, Rockwell International Corporation Missiles Systems Division, Wright-Patterson AFB, OH.

The concept and philosophy for the organization of an RPV Flying Qualities Design Criteria are presented in a preliminary framework of criteria with supporting background and rationale. This report completes Phase II 6f a four-phase AFFPL/FGC program for the development of an RPV Flying Qualities Specification. The performance-oriented criteria are developed in hierarchical fashion from mission requirements, through total system requirements, to subsystem requirements. The criteria encompass automatic and manual controls, command and data link, controls and displays as well as vehicle stability and control. The material was based on an RPV literature search and review, and an evaluation of existing military specifications for piloted aircraft, such as MIL-F-8785B, MIL-F-83300, MIL-F-9490D (USAF), and MIL-C-18244A (Navy).

Proudian, A. P., Balser, M.

"AIRCRAFT VORTEX DETECTION SYSTEM"

US Patent 3,671,927, June 1972.

A system for detection and measurement of aircraft wing tip vortices. An acoustic radar with transmitter and receiver spaced from each other in a plane perpendicular to the flight path for illuminating the vortex and picking up scattering of the transmitter signal produced by the vortex, using Doppler frequency spectrum analysis with the maximum and minimum frequencies providing a measure of vortex intensity. A plurality of receivers operating with a common transmitter providing coverage of an area of interest along a flight path.

Pruis, M. J. and Delisi, D. D

"CORRELATION OF THE TEMPORAL VARIABILITY IN THE CROSSWIND AND THE OBSERVATION LIFETIME OF VORTICES MEASURED WITH A PULSED LIDAR"

AIAA Paper No. 2011-3199, June 2011, Honolulu, Hawaii.

The length of time over which a vortex pair behind a generating aircraft is observed with a pulsed lidar is compared with the observed temporal variability of the local crosswind. Multiple aircraft types and a broad range of atmospheric conditions are examined. It is found that the observed variability of the crosswind is a strong predictor of the observation lifetime. The magnitude of the variability of the crosswind varies as a function of time, measurement sites and altitude, but the relationship between the observation lifetime and temporal crosswind variability appears to be robust in the out-of-ground effect region. The focus of this paper is on results from a 2006 measurement campaign at Denver International Airport; however, the methodology is applicable at other airports. We compare these results with EDR estimates obtained using tower measurements and describe a new methodology for estimating EDR using the velocity estimates obtained from the same pulsed lidar that is used to track the vortices.

Pruis, M. J. and Delisi, D. P

"COMPARISON OF ENSEMBLE PREDICTIONS OF A NEW PROBABILISTIC FAST-TIME WAKE VORTEX MODEL AND LIDAR OBSERVED VORTEX CIRCULATION INTENSITIES AND TRAJECTORIES"

AIAA Paper No. 2011-3036, June 2011, Honolulu, Hawaii.

Lidar observations of wake vortex circulation intensity and trajectories are compared to the predictions of a new probabilistic fast-time wake vortex model. The new probabilistic model utilizes several different deterministic fast-time vortex models and produces ensemble model predictions of wake vortex behavior. Multiple numerical predictions are conducted in the form of a Monte Carlo analysis with slightly different initial conditions that are all plausible given the past or current set of observations and measurements. The probabilistic model predictions attempt to account for the two primary sources of uncertainty in fast-time wake vortex models: the errors introduced by sensitivity to the initial aircraft parameters and environmental conditions; and errors introduced because of imperfections in the model assumptions and simplifications. There three main findings of the study. First, the new probabilistic fast-time wake vortex prediction model reproduces observed vortex behavior and predicts approximately the same mean and spread as the observations. Second, uncertainties in the generator aircraft parameters are as important as uncertainties in the atmospheric conditions in generating estimated spread in the model predictions. And third, the spread between the different deterministic fast-time wake vortex models overlaps when plausible uncertainties in initial conditions are used. While development and validation of the new probabilistic fast-time wake vortex model is on-going, it appears that it will develop into a useful tool to help assess deterministic fast-time model performance, to assist in planning future wake vortex field observation campaigns, and eventually to examine current or proposed wake separation standards.

Pruis, M. J. and Delisi, D. P.

"ASSESSMENT OF FAST-TIME WAKE VORTEX PREDICTION MODELS USING PULSED AND CONTINUOUS WAVE LIDAR OBSERVATIONS AT SEVERAL DIFFERENT AIRPORTS"

AIAA Paper No. 2011-3035, June 2011, Honolulu, Hawaii.

Seven fast-time numerical wake vortex prediction models are reviewed, compared against each other, and evaluated against observations obtained using pulsed and continuous wave lidar at several different airports. Assessment of the models is performed as a function of wake age, aircraft size, generator height, and environmental conditions. The purpose of this study is to assess the relative strengths and weaknesses and ranges of applicability of different fast-time wake vortex prediction models. An important finding of this study is that, over a large range of environmental conditions, the fast-time wake vortex models predict similar behavior in vortex trajectories and circulation intensity. Furthermore, evaluation of the models with lidar observations indicates that in this same range of environmental conditions, the models agree reasonably well with observations of wake vortex evolution. The largest spread in the model predictions occur when the ambient turbulence is weak. Importantly, these conditions correlate with the long-lasting wake vortex observations. Increasing stratification also increases the model spread. Unfortunately, there is a paucity of available high quality, in situ observations of environmental conditions coincident with wake vortex measurements. The lack of high-quality data leads to ambiguity in ranking model performance. Assessment would be improved by a better quantification of the errors and uncertainties in the lidar observations, atmospheric conditions, and aircraft parameters; and with more landings in different glide slope regions with high quality, in situ observations of environmental conditions.

Pruis, M. J., Delisi, D. P. and Ahmad, N. N.

"COMPARISONS OF CROSSWIND VELOCITY PROFILE ESTIMATES USED IN FAST-TIME WAKE VORTEX PREDICTION MODELS"

AIAA Paper No. 2011-1002, January 2011, Orlando, FL.

Five methods for estimating crosswind profiles used in fast-time wake vortex prediction models are compared in this study. Previous investigations have shown that temporal and spatial variations in the crosswind vertical profile have a large impact on the transport and time evolution of the trailing vortex pair. The most important crosswind parameters are the magnitude of the crosswind and the gradient in the crosswind shear. It is known that pulsed and continuous wave lidar measurements can provide good estimates of the wind profile in the vicinity of airports. In this study comparisons are made between estimates of the crosswind profiles from a priori information on the trajectory of the vortex pair as well as crosswind profiles derived from different sensors and a regional numerical weather prediction model.

Pruis, M. J., Delisi, D. P. and Jacob, D.

"EFFECT OF ATMOSPHERIC SHEETS AND LAYERS NEAR THE GROUND ON WAKE VORTEX TRANSPORT AND DECAY"

AIAA Paper 2015-3315, June 2015, Dallas, TX.

Sheets and layers in the atmospheric boundary layer are common and develop during nighttime stably stratified shear flows. The eddy dissipation rates in the layers are found to be 3 to 4 orders of

magnitude less than the sheets between the layers, a difference large enough to potentially modify the rate at which vortices decay. The sheets are also found to be the boundaries separating regions of vorticity. Thus depending on what layer the aircraft vortex is horizontally advected within, the ambient vorticity of the region may reinforce or oppose the vorticity of the wake vortex. The vertical crosswind shear that is correlated with the presence of sheets and layers will also tend to tilt the port and starboard vortices with respect to one another, and thus it is not uncommon for the vortices to be horizontally advected at heights that are different from one another. We believe that because of the combination of these processes, vortices may sometimes be observed propagating in a layer of reduced turbulence for a longer than expected amount of time. In this paper, we will describe data collected at Memphis International Airport and show examples of vortices descending through atmospheric sheets and layers.

Pruis, M. J., Delisi, D. P. and Jacob, D.

"OBSERVATIONS OF WAKE VORTICES FROM UPWARD LOOKING PULSED DOPPLER LIDAR DATA"

AIAA Paper 2015-3177, June 2015, Dallas, TX.

NASA collected a large dataset of wake vortex and weather observations at Memphis International Airport from the spring of 2013 through early 2015. During this field experiment, there were several time intervals where special data acquisitions were obtained. One of these special data acquisitions is upward looking vertical stare data obtained using NASA's Halo Photonics StreamLine pulsed Doppler lidar. The upward looking stare data was collected in regions where wake vortices generated behind aircraft would drift with the ambient crosswind past the lidar. Samples of data from both arriving and departing aircraft were obtained. These observations were collected as experiments of opportunity, however from the preliminary analysis of the data, we believe it will be possible to obtain estimates of the core radius of the vortices, the distance between the vortex cores, and the tangential velocity profile of the vortices from this type of data product. In this paper, we will discuss the field set-up for these observations, review the data processing techniques and discuss the potential for these types of observations to estimate wake parameters that are currently not well constrained, yet very important, for development of wake hazard metrics.

Pruis, M. J., Delisi, D. P. and Jacob, D.

"OBSERVATIONS OF SMALL-SCALE ATMOSPHERIC VARIABILITY AND THE IMPORTANCE OF ACCURATE WEATHER INFORMATION IN DETERMINISTIC AND PROBABILISTIC FAST-TIME WAKE VORTEX MODELING"

AIAA Paper 2014-2468, June 2014, Atlanta, GA.

NASA has an on-going field experiment at Memphis International Airport to measure wake turbulence generated by aircraft in the near-ground effect region. This new data will be used in the validation and improvement of fast-time numerical wake vortex models, and provide an important data set to be used in the further development of probabilistic wake vortex estimation algorithms. An important component of this field program is to obtain high-quality estimates of important weather conditions in,

or near, the region where the wake vortices are generated and tracked, and at a frequency such that the scales of variability important in the evolution of wake vortices is observed. In this paper we will describe the intercomparisons of the estimates derived from multiple sensors for the important weather parameters of atmospheric turbulence and wind speed and direction. Using the results of this intercomparison, we will provide some guidance on what uncertainties may be applicable and useful when utilizing different sources for the estimation of the meteorological condition in probabilistic fast-time wake vortex simulations.

Pruis, M. J., Delisi, D. P., Ahmad, N. N. and Proctor, F. H.

"ATMOSPHERIC TURBULENCE ESTIMATES FROM A PULSED LIDAR"

AIAA Paper 2013-0512, January 2013, Grapevine, TX.

Estimates of the eddy dissipation rate (EDR) were obtained from measurements made by a coherent pulsed lidar and compared with estimates from mesoscale model simulations and measurements from an in situ sonic anemometer at the Denver International Airport and with EDR estimates from the last observation time of the trailing vortex pair. The estimates of EDR from the lidar were obtained using two different methodologies. The two methodologies show consistent estimates of the vertical profiles. Comparison of EDR derived from the Weather Research and Forecast (WRF) mesoscale model with the in situ lidar estimates show good agreement during the daytime convective boundary layer, but the WRF simulations tend to overestimate EDR during the nighttime. The EDR estimates from a sonic anemometer located at 7.3 meters above ground level are approximately one order of magnitude greater than both the WRF and lidar estimates -- which are from greater heights -- during the daytime convective boundary layer and substantially greater during the nighttime stable boundary layer. The consistency of the EDR estimates from different methods suggests a reasonable ability to estimate, from pulsed lidar measurements, the EDR near and below the altitude of an aircraft in an airport terminal area.

Pruis, M. J., Delisi, D. P., Jacob, D. and Lai, D. Y.

"FAST-TIME WAKE VORTEX MODEL PREDICTIONS COMPARED WITH OBSERVATIONS BEHIND LANDING AIRCRAFT NEAR THE GROUND"

AIAA Paper 2015-3316, June 2015, Dallas, TX.

NASA has recently collected a large dataset of wake vortex and weather observations at Memphis International Airport. The wake data consists primarily of vortices generated between one and two wingspans above the ground. Most of the landings in the dataset include field observations of all the required environmental and aircraft data needed for input into fast-time wake vortex prediction models: including vertical profiles of wind speed, air temperature and eddy dissipation rate, as well as the aircraft weights. Prior to the collection of this data set there was only a small amount of data that could be used in the evaluation of the skill of fast-time wake vortex prediction models when the vortices were generated within a couple wingspans of ground surface. This new data set significantly

increases the amount of data available for the assessment of the models in this important region. Comparison of three fast-time model predictions with the new Memphis data indicates there are several areas where the models can be improved in the in-ground effect region; specifically better parameterization of the effect of turbulence, and inclusion of the effect of headwind.

Pruis, M. J., Delisi, D. P., Jacob, D. and Lai, D. Y.

"SUMMARY OF NASA WAKE AND WEATHER DATA COLLECTION AT MEMPHIS INTERNATIONAL AIRPORT: 2013-2015"

AIAA Paper 2016-3274, June 2016, Washington, DC.

NASA has collected a large dataset of wake vortex and weather observations at Memphis International Airport. The wake data consists primarily of vortices generated between one and two wingspans above the ground. Most of the landings in the dataset include all the required environmental and aircraft data needed for input into fast-time wake vortex prediction models; including vertical profiles of wind speed, air temperature and eddy dissipation rate, as well as the aircraft weights and approach speed. Prior to the collection of this data set there was only a small amount of data that could be used in the evaluation of the skill of fast-time wake vortex prediction models when the vortices were generated within a couple wingspans of the ground surface. This new data set significantly increases the amount of data available for the assessment of the models in this important region. In this paper, we will describe the new data set including how the environmental data was collected and analyzed, and show example results comparing wake vortex behavior for different atmospheric conditions and aircraft types.

Pruyn, R. and Goland, L.

"AN INVESTIGATION OF VTOL OPERATIONAL PROBLEMS DUE TO DOWNWASH EFFECTS"

Report 179T80-2, June 1961, Kellett Aircraft, Willow Grove, PA.

Operational problems of VTOL type aircraft caused by downwash effects have been investigated utilizing a 3500-horsepower engine and a 15-foot diameter propeller mounted on a 20-ton crane. Results are presented for various propeller disc loadings up to 60 pounds per square foot, for several types of terrain and for various propeller heights and orientation above the terrain. The effects on pilot vision, ground personnel, equipment, aircraft and on aircraft concealment are presented. The effects of downwash were found to be a major operational problem which could limit the operational utility of VTOL aircraft.

Pruzan, D. A.

"EVALUATION OF AN ULTRASONIC VORTEX DETECTION SYSTEM"

AIAA Paper No. 2005-1413, Reno, NV, January 2005

Nielsen Engineering and Research (NEAR) has developed a prototype ultrasonic vortex detection system for measuring axial vorticity in a turbine engine test cell. To detect the presence of vorticity, acoustic signals are propagated around the inside perimeter of the test cell's bell mouth. An ultrasonic transmitter, flush-mounted with the bell mouth wall, generates an acoustic pulse which travels around the bell mouth along a path nominally perpendicular to the freestream direction. The propagation time for this signal to get to the receiver is then measured. The transmitter and receiver functions are then switched, and the time-of-flight for propagation in the opposite direction is measured. If there is no axial vorticity present, the two measured time-of-flight values will be the same. If the two measurements differ, then there is vorticity in the flow, and the associated circulation value can be directly computed from the time-of-flight measurements and knowledge of the local speed of sound. To demonstrate the feasibility of this approach, a prototype of the ultrasonic vortex detection system was fabricated and installed into a 10-inch diameter, low-speed wind tunnel. Measurements of vorticity were made with the tunnel empty, and with a low-aspect ratio wing present to generate axial vorticity. The latter measurements compare well with predicted wing tip vorticity values from NEAR's MISDL numerical code.

Puel, F. and de Saint Victor, X.

"INTERACTION OF WAKE VORTICES WITH THE GROUND"

Aerospace Science and Technology, Vol. 4, March 2000, pp. 239-247

The aim of this study is to describe wake vortices near the ground, including rebound. A calculation code solving the incompressible Navier-Stokes equations has been developed; it allows us to compute unsteady two-dimensional flows and steady three-dimensional flows having a preferential direction. The two-dimensional version of the code allows the capture of the rebound of the vortices near the wall as well as the creation of secondary vortices. In the three-dimensional case, the results are compared with experiments. The importance of the axial velocity is also analyzed.

Pulla, D.

"THE UNSTEADY WAKE GOVERNED BY A ROTOR IN GROUND EFFECT"

American Physical Society, 57th Annual Meeting Division of Fluid Mechanics, Nov. 2005, Chicago, IL.

Helicopters flying close to the ground encounter many handling qualities problems. Large unsteady forces near the main and tail rotors are believed to be a major cause of these problems. We investigate the structure of the unsteady wake generated by multibladed rotors in ground effect. A vortex lattice method with a free wake model is used to simulate the tip-vortex and the method of images is used to model the ground and the blades are modeled using the lifting surface method. The rotor wake is advanced in time until periodicity is attained. Unsteadiness in the form of instantaneous velocities is studied at different planes on the advancing and retreating sides of the tail rotor to identify the plane with the maximum unsteadiness. The root-mean-square of the deviation of the instantaneous velocity from the time averaged velocity over a given period is used to quantify the unsteadiness.

Pulla, D. and Conlisk, A. T.

"THE LONG TIME STRUCTURE OF THE ROTOR WAKE IN GROUND EFFECT"

AIAA Paper No. 2005-1408, Reno, NV, January 2005

The form of the rotor wake in the presence of a ground has been investigated using a vortex model of the rotor wake. Both hover and forward flight have been considered and the presence of the ground is modelled using the method of images. A lifting-line theory is used to model the rotor blade and a time-stepping vortex method has been used to obtain the evolution of tip-vortex. A numerical scheme has been designed to compute up to a hundred rotor revolutions. Our results show that periodicity is obtained after about thirty rotor revolutions near the blade as well as near the ground although this value depends to some extent on the advance ratio. Unsteadiness near the tail rotor has been studied by computing the deviation of the downwash and y -velocities from the mean at a hypothetical tail rotor and on its advancing and retreating sides.

Pulla, D. P.

"A STUDY OF HELICOPTER AERODYNAMICS IN GROUND EFFECT"

PhD Thesis, May 2006, Ohio State University, Columbus, OH.

The flow around a helicopter is very complex; it becomes much more complex when it comes close to the ground. The presence of the ground changes the aerodynamic characteristics of the rotor and the flow environment becomes much more complex compared with that of flight out-of-ground effect and hence the behavior of the rotor wake in the vicinity of the ground is challenging to predict. Under in-ground-effect conditions, the wake collides with the ground and causes a significant perturbation to the flow near the blade. Significant interactions between the main rotor wake and the ground have been associated with the formation and passage of the ground vortex in forward flight. The presence of a ground vortex affects the handling qualities of the helicopter. The aim of this research is to capture the physics of the flow features and dynamics of ground effect flows around a rotorcraft, provide an understanding of the rotor wake/vortices near the ground, and generate rigorous models to accurately predict handling qualities, loads and moments acting on the rotor and the power requirements. The wake structure after periodicity is reached is obtained for hover and different forward flight speeds. Also, the nature of the flowfield, as well as the formation of the ground vortex, is understood by obtaining the velocity contours on a longitudinal plane containing the rotor blade after periodicity is obtained. The unsteadiness in the velocities is quantified by obtaining the RMS deviation in velocities on different planes containing the tail rotor around the rotor disk simulating the various kinds of flight. Thrust and power requirements on the rotor disk have been predicted and have been successfully validated by comparison with experimental results obtained from Georgia Institute of Technology.

Pulla, D. P., Godavarty, V., Burgraff, O. R. and Conlisk, A. T.

"INVISCID MODEL OF THE FORMATION OF A ROTOR TIP VORTEX"

AIAA Journal, Vol. 44, No. 7, July 2006, pp. 1653-1661.

The roll up of trailing vortex filaments shed from a finite-length rotor blade in hover has been computed and analyzed. It is shown that the formation of the tip vortex is a strong function of the aspect ratio of the blade, angle of attack, and number of blades. The amount of trailing circulation associated with the tip vortex develops downstream and approaches an asymptotic constant that is less than that the total amount of trailing circulation. The results for the vertical and horizontal velocity profiles downstream of the blade are compared with the results for an infinite blade and with the experimental results of McAlister et al, (McAlister, K., Tung, C., and Heineck, J. T., 'Devices That Alter the Tip Vortex of a Rotor' NASA TM-2001-209625, Aeroflightdynamics Directorate, TR-01-A-003, Feb. 2001). The velocity profiles across the tip vortex compare extremely well with experiment.

Pulla, P., Bhattacharyya, S. and Conlisk, A. T.

"THE STRUCTURE OF THE ROTOR WAKE IN GROUND EFFECT"

American Physical Society, Fluid Dynamics 56th Annual Meeting, Nov. 2003, East Rutherford, NJ.

The form of the rotor wake in the presence of a ground has been investigated. Both hover and forward flight have been considered. The presence of the ground is modeled using the method of images. Lifting-line and lifting surface methods have been used to model the blade and results for the two methods are compared. A time-stepping vortex method has been used to obtain the evolution of tip-vortex. The agreement of the computed results with experimental data in hover is encouraging. The wake geometry for both single and two bladed rotors has been calculated for different ground to rotor separation distances and for several forward flight speeds. The individual vortex lines comprising the tip vortices form the ground vortex on the upstream side of the rotor at low forward flight speeds. The results show that the vortex core shifts downstream as the forward speed of the rotor increases.

Pullin, D. I. and Phillips, W. R. C.

"ON A GENERALIZATION OF KADEN'S PROBLEM"

Journal of Fluid Mechanics, Vol. 104, March 1981, pp. 45-53.

Kaden's problem of the roll-up of an initially planar semi-infinite vortex sheet is extended to include sheets exhibiting a general power law circulation distribution resulting in both power law and logarithmic-like velocity field singularities. Both single and double branched spirals are considered.

Pullin, D. I. and Saffman, P. G.

"VORTEX DYNAMICS IN TURBULENCE"

Ann. Rev. Fluid Mechanics, Vol. 30, 1998, pp. 31-51

We survey attempts to construct vortex models of the inertial-range and fine-scale range of high Reynolds number turbulence. An emphasis is placed on models capable of quantitative predictions or post-dictions.

Purser, P. E., Spearman, M. L. and Bates, W. R.

"PRELIMINARY INVESTIGATION AT LOW SPEED OF DOWNWASH CHARACTERISTICS OF SMALL-SCALE SWEPTBACK WINGS"

NACA Technical Note, 1378, July 1947, Langley Memorial Aeronautical Laboratory, Langley Field, VA.

A preliminary investigation has been made at low speed of the downwash behind various small-scale sweptback wings. The wing configurations for which data were obtained covered aspect ratios from 2.5 to 4.0, sweepback angles from 32.5 to 40 degrees, and ratios of root chord to tip chord from 0.62 to 2.06. The data showed that for the higher tails and shorter tail lengths behind each of the wings in the wing-tail combinations tested, fairly large variations occurred in the rate of change of downwash angle with angle of attack de/da at high angles of attack with resulting large changes in the longitudinal stability of the wing-tail combinations. In general, lowering the tail to a position near the extended chord line of the wing and increasing the tail length caused improvement of the stability as characterized by decreases in de/da and by decreases in the variation of de/da with angle of attack. Increasing the wing aspect ratio caused a reduction in de/da and improved the tail contribution to the stability. Increasing the ratio of wing root chord to tip chord caused increases in the rate of change of downwash angle with angle of attack for the low lift range. The use of trailing-edge flaps caused a slight increase in de/da and caused an increment of downwash angle at low angles of attack about the same as would be expected for unswept wings. Leading-edge slats reduced the variation of de/da at high lift coefficients and generally resulted in improvement of the stability. Values of downwash angle computed from design charts for unswept wings given in NACA Reports No. 648 and 711 agreed fairly well with experimental data at low lift coefficients provided the computations were based on the aspect ratio and span of an unswept wing having the same panels as the sweptback wing.

Purvis, J. W.

"ANALYTICAL PREDICTION OF VORTEX LIFT"

J. Aircraft, Vol. 18, No. 4, April 1981, pp. 225-230

General integral expressions are derived for the nonlinear lift and pitching moment of arbitrary wing planforms in subsonic flow. The analysis uses the suction analogy and an assumed pressure distribution based on classical linear theory results. The potential flow lift constant and certain wing geometric parameters are the only unknowns in the integral expressions. Results of the analysis are compared with experimental data and other numerical methods for several representative wings, including ogee and double-delta planforms. The present method is shown to be as accurate as other numerical schemes for predicting total lift, induced drag, and pitching moment.

Puttinger, S., Mehrle, A. and Gittler, P.

"NUMERICAL OPTIMIZATION AND EXPERIMENTAL INVESTIGATIONS ON THE PRINCIPLE OF THE VORTEX DIFFUSER"

AIAA Paper No. 2009-3610, June 2009, San Antonio, Texas.

The present work deals with numerical optimization of and experimental studies on aft mounted wing tip devices, so called vortex diffusers. The purpose of most kinds of wing tip devices is to reduce the induced drag by converting vortex energy into thrust. To obtain an optimal design for the vortex diffuser, the parameterized diffuser blade shape is optimized with respect to axial thrust within the framework of lifting line theory. Finite airfoil performance is accounted for by applying lift and drag coefficients from wind tunnel data. The so gained optimal design for the vortex diffuser blades is realized on a small-scale model, and wind tunnel tests are carried out to investigate drag reduction of the vortex diffuser for comparison with numerical results. Furthermore, the goal is to gain some experience and data for preparation of real flight testing on a UAV. Experiments clearly show that the vortex diffuser can reduce drag in high lift / high angle of attack configurations. Wind tunnel tests, however, also demonstrate some problems for practical design of the vortex diffuser.

Qiao, W. and Michel, U.

"A STUDY ON THE VORTEX SHEDDING NOISE FROM THE WAKE OF AIRCRAFT WINGS"

AIAA Paper No. 2000-1973, Lahaina, HI, June 2000

An important airframe noise source -vortex shedding noise- was first identified by U. Michel et al (1998) based on the fly-over measurements with a planar microphone array. In this paper, the detail results from the planar microphone array measurements about this new airframe noise source on different aircraft were presented. The position of this source on airframe, the frequency features and the directional features of this source were described. It is found that the narrow-band frequency spectrum of this source is dominated by a tone. The frequency of the tone increases with the increase in airspeed. The directivity of the tone has an increasing sound pressure level to the forward arc, and a decreasing sound pressure level to the rear arc. The difference of the sound pressure level from emission angle of 60 degrees to 120 degrees is about 5-8 dB. It is proposed that vortex shedding from the wake of aircraft wing results to this noise surface.

Qiao, Z. D., Yang, A. M. and Zhu, B.

"NUMERICAL SIMULATION OF NAVIER-STOKES EQUATIONS FOR HELICOPTER ROTOR IN FORWARD FLIGHT USING MOVING CHIMERA GRIDS"

ICAS 2002 Paper 2002-R53, Sopt. 2002, Toronto, Canada.

At present dual time methods with explicit inner iteration scheme have been adopted by the most of unsteady flow simulations based on Euler equations or Navier-Stokes equations. A disadvantage of the methods is that the computation efficiency is not enough to calculate the complex unsteady flows. In

this paper a full implicit dual time method with implicit pseudo-time scheme by using moving chimera grids is developed for computation of complex unsteady flows. In the method a highly efficient implicit LU-SSOR method is adopted for the inner interaction computation. The numerical tests of the unsteady flow simulation based on Navier-Stokes equations for forward flight of rotary wings show that the computation results agree with experiment and the method is very efficient for computation of complex unsteady flows.

Qu, Q., Huang, L., Liu, P. and Agarwal, R. K.

"NEAR-FIELD WINGTIP VORTEX CHARACTERISTICS OF A RECTANGULAR WING IN GROUND EFFECT"

AIAA Paper 2016-1781, January 2016, San Diego, CA.

The aerodynamics and near-field wingtip vortex characteristics of a rectangular wing with NACA4412 section in ground effect (GE) are studied in this paper. The steady compressible Reynolds-Averaged Navier-Stokes (RANS) equations with the Spalart-Allmaras (SA) turbulence model are discretized using the finite volume method. Based on the pressure and lift variations in GE, a 3D rectangular wing can be divided into two parts along the span-wise direction: the quasi-2D inner part of the wing (away from wing tip) in which the lift increases monotonously, and the second part near the wingtip in which the lift decreases. In GE, the wingtip vortex moves outward along the span-wise direction due to the ground mirror effect, and rebounds in the vertical direction due to the induction from the secondary vortex generated from the ground boundary layer. In GE, the strength of the near-field wingtip vortex along the flow direction depends not only on the initial vortex strength and the shear layer developing from the trailing edge of the wing, but also due to the generation of secondary vortex in the ground boundary layer, and the interaction between the wingtip vortex and the secondary vortex.

Qu, Q., Lv, C., Liu, P. and Agarwal, R. K.

"DETACHED EDDY SIMULATION OF FAR-FIELD WAKE VORTEX IN STATIC AND MUTATIONAL GROUND EFFECTS"

AIAA Paper 2017-3039, June 2017, Denver, CO.

Far-field wake vortex can increase the risk in take-off and landing of a fighter aircraft especially on the deck of an aircraft carrier. The development and decay of a far-field wake vortex in static and mutational ground effect is studied using the detached eddy simulation (DES). Without loss of generality, in this study the vortex is modeled as an Oseen vortex. In the quiescent air, the Oseen vortex moves closer to the ground or moves over the platform. The vortex decay in unbounded flow field is slower due to viscous effects. It is shown by numerical simulation that the vortex decay in static ground effect is very quick due to both the secondary vortex generation and the interaction between the primary vortex and the secondary vortex.

Quackenbush, T. R. and Wachspress, D. A.

"REVIEW AND ASSESSMENT OF SELECTED ISSUES IN HOVERING ROTOR TIP VORTEX DYNAMICS"

Proceedings of the ARO Rotorcraft Wake Prediction Basic Research Workshop, March 2009, Georgia Institute of Technology, Atlanta, GA, p. 50.

This discussion will briefly outline previously developed (though still relevant) methods of analysis of vortex instabilities in hovering rotor wakes, derived from the linearized dynamics of self-preserving wake solutions. The behavior of OGE rotor wakes will be discussed and the relationship of computed measures of wake instabilities to prior analytical and experimental results from other investigators will be noted. The ability of current methods to capture noteworthy behaviors in the wakes of IGE hovering rotors will also be described, including the appearance of long-period pulsations in wake-induced velocity and vortex bundling.

Quackenbush, T. R., Batcho, P. F., Bilanin, A. J. and Carpenter, B. F.

"DESIGN, FABRICATION, AND TEST PLANNING FOR AN SMA-ACTUATED VORTEX WAKE CONTROL SYSTEM"

Proc. SPIE, Vol. 3326, June 1998, pp. 259-27.

This paper describes ongoing design and fabrication work on a vortex wake control system for submarines that employs SMA-actuated devices. Previous work has described the theoretical basis and feasibility studies for this system, which is based on a novel wake control scheme known as vortex leveraging. The critical item in the realization of this system is a Smart Vortex Leveraging Tab (SVLT), whose design and fabrication is the principal focus of this work. This paper outlines the background of the effort and the design principles involved, but will chiefly deal with three closely interrelated topics; the hydrodynamic design requirements and control surface layout for the vortex leveraging system; the detail design and fabrication techniques being used in the construction of a prototype SVLT; and the test planning and experiment design process currently underway for test of both the overall vortex leveraging concept and SVLT device itself.

Quackenbush, T. R., Bilanin, A. J. and Carpenter, B. F.

"TEST RESULTS FOR AN SMA-ACTUATED VORTEX WAKE CONTROL SYSTEM"

Proceedings SPIE, Industrial and Commercial Applications of Smart Structures Technologies, Vol. 3674, March 1999, Newport Beach, CA, pp. 84-94.

This paper describes recent test results obtained on a prototype SMA-actuated foil that serves as a key element in a vortex wake control scheme for lifting surfaces. Previous papers have described the theoretical basis and feasibility studies for this scheme -- which is based on a novel wake control concept known as vortex leveraging -- as well as prior work on device design, test planning, and fabrication. The critical item in the realization of this scheme is a Smart Vortex Leveraging Tab (SVLT), a device designed to provide perturbations in the vortex system downstream of lifting surfaces at frequencies and amplitudes carefully selected to accelerate overall wake breakup. The paper

summarizes the background of the effort, but focuses on the detailed design and fabrication techniques used in the construction of a prototype SVLT and the results of water tunnel tests of a near full-scale prototype device.

Quackenbush, T. R., Bilanin, A. J. and McKillip, R. M.

"VORTEX WAKE CONTROL VIA SMART STRUCTURES TECHNOLOGY"

Proc. SPIE, Vol. 2721, May 1996, pp. 78-92

Control of trailing vortex wakes is an important challenge for both military and civilian applications. This paper summarizes an assessment of the feasibility of mitigating adverse vortex wake effects using control surfaces actuated via Shape Memory Alloy (SMA) technology. The assessment involved a combined computational/design analysis that identified methods for introducing small secondary vortices to promote the deintensification of vortex wakes of submarines and aircraft. Computational analyses of wake breakup using this 'vortex leveraging' strategy were undertaken, and showed dramatic increases in the dissipation rate of concentrated vortex wakes. This paper briefly summarizes these results and describes the preliminary design of actuation mechanisms for the deflectable surfaces that effect the required time-varying wake perturbations. These surfaces, which build on the high-force, high-deflection capabilities of SMA materials, are shown to be well suited for the very low frequency actuation requirements of the wake deintensification mission. The paper outlines the assessment of device performance capabilities and describes the sizing studies undertaken for full-scale Vortex Leveraging Tabs (VLTs) designed for use in hydrodynamic and aerodynamic applications. Results obtained to date indicate that the proposed VLTs can accelerate wake breakup by over a factor of three and can be implemented using deflectable surfaces actuated using SMAs.

Quackenbush, T. R., Bilanin, A. J., Batcho, P. F., McKillip, R. M. and Carpenter, B. F.

"IMPLEMENTATION OF VORTEX WAKE CONTROL USING SMA-ACTUATED DEVICES"

Proc. SPIE, Vol. 3044, May 1997, pp. 134-146

Mitigation of the undesirable effects of trailing vortex wakes has been a long-standing priority for both reduction of submarine wake signature and alleviation of aircraft vortex wake hazard. A recent study established the feasibility of using relatively weak, secondary vortices with carefully selected unsteady amplitude and phasing to accelerate the breakup of the primary vortex system of a lifting surface, a technique denoted 'vortex leveraging'. This paper will summarize progress on the development of SMA-actuated devices for implementing vortex leveraging for hydrodynamic applications. The methods being applied to the hydrodynamic design of these deformable Smart Vortex Leveraging Tabs (SVLTs) will be described, and the results of a preliminary assessment of SVLT performance in achieving wake breakup will be presented. Also, previous work on the design and testing of deformable control surfaces actuated via embedded SMA agonist wires will be reviewed and the design process being employed in the present applications will be discussed. Finally, the plans for

near-term computational and experimental work to validate the use of SMA-driven devices for the wake mitigation task will be briefly outlined.

Quackenbush, T. R., Boschitsch, A. H. and Bilanin, A. J.

"COMPUTATIONAL AND EXPERIMENTAL STUDIES IN MULTIPAIR WAKE VORTEX INSTABILITIES"

AIAA Paper 2013-3190, June 2013, San Diego, CA.

Control of trailing vortex wakes of lifting surfaces such as aircraft wings and submarine control planes is an important challenge for both military and civil applications. This paper summarizes the development and testing of a method for mitigating adverse vortex wake effects using active control of auxiliary aerodynamic surfaces mounted on the primary lifting wing. The governing concept involves a method for introducing small, secondary vortices of periodic, time-varying strength to promote the deintensification of the primary vortex wake system. Computational analyses of wake breakup using this 'vortex leveraging' strategy have shown up to an order of magnitude increase in the dissipation rate of concentrated vortex pair wakes relative to natural mechanisms. The work described here was among the first efforts to explore this class of mitigation methods and the discussion below summarizes the foundational analysis and validation work on this concept. Computational modeling involved application of fast vortex methods to identify potentially promising methods for exploiting the instabilities of multipair vortex wakes. Validation of the concept was done by way of tow tank experiments that both provided flow visualization of predicted wake on wake interactions and measurements of vortex transport indicating substantial mitigation of wake effects.

Quackenbush, T. R., Boschitsch, A. H. and Bilanin, A. J.

"ASSESSMENT OF AIRCRAFT AND ROTORCRAFT WAKE FLOW FIELDS FOR WAKE HAZARD APPLICATIONS"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

NASA has identified the objective of tripling airport throughput over the next decade as an air transport goal, and a likely major component of such an effort is the utilization of rotorcraft to provide feeder service to major airports. Among the key challenges in ensuring safe, high-volume terminal area rotorcraft operations are identifying and mitigating potential hazards posed by vortex encounters between rotorcraft and fixed wing aircraft. To address these challenges, a family of fast yet high-fidelity vortex wake modeling methods must be developed for eventual incorporation into both off-line assessment tools and pilot-in-the-loop simulation environments. Though considerable additional technology development is required, several elements of a hierarchy of physics-based models for assessment of a range of possible encounter scenarios are currently in hand. This paper will review the development status of these models and examine key features of the predicted flow fields, particularly with respect to the likely impact of wake-induced forces and moments on the flight dynamics of nearby aircraft. Also described are databases suitable for model validation as well as further technology

developments that are likely necessary to address the full range of complex aeromechanical phenomena in future terminal area operations environments.

Quackenbush, T. R., Teske, M. E. and Bilanin, A. J.

"DYNAMICS OF EXHAUST PLUME ENTRAINMENT IN AIRCRAFT VORTEX WAKES"

AIAA Paper No. 1996-0747, Reno, NV, January 1996

The prediction of wake/exhaust mixing for subsonic and supersonic aircraft is an important aspect of the assessment of the atmospheric effects of aviation. This paper focuses on the development, modification, and testing of analysis methods for the specific application of predicting the mixing of the aircraft vortex wake with the engine exhaust. The case studies described indicate the importance of buoyancy and variable density effects in realistic simulations, and having helped quantify important differences in plume entrainment and detrainment between major classes of commercial aircraft.

Quackenbush, T. R., Teske, M. E. and Bilanin, A. J.

"COMPUTATION OF WAKE/EXHAUST MIXING DOWNSTREAM OF ADVANCED TRANSPORT AIRCRAFT"

AIAA Paper 93-2944, July 1993, Orlando, FL.

The mixing of engine exhaust with the vortical wake of high speed aircraft operating in the stratosphere can play an important role in the formation of chemical products that deplete atmospheric ozone. An accurate analysis of this type of interaction is therefore necessary as a part of the assessment of the impact of proposed High Speed Civil Transport (HSCT) designs on atmospheric chemistry. This paper describes modifications to the parabolic Navier-Stokes flow field analysis in the UNIWAKE unified aircraft wake model to accommodate the computation of wake/exhaust mixing and the simulation of reacting flow. The present implementation uses a passive chemistry model in which the reacting species are convected and diffused by the fluid dynamic solution but in which the evolution of the species does not affect the flow field. The resulting analysis, UNIWAKE/PCHEM (Passive CHEMistry) has been applied to the analysis of wake/exhaust flows downstream of representative HSCT configurations. The major elements of the flow field model are described, as are the results of sample calculations illustrating the behavior of the thermal exhaust plume and the production of species important to the modeling of condensation in the wake. Appropriate steps for further development of the UNIWAKE/PCHEM model are also outlined.

Querin, O. M.

"ROTOR WAKE INVESTIGATION USING THE SMOKE FLOW VISUALIZATION TECHNIQUE"

MS Thesis, March 1993, University of Sidney, Sidney, Australia.

Experiments were carried out on a small four bladed rotor at different climb rates. The smoke-filament technique was used to visualize the rotor tip vortices; video equipment was then used to

record the images produced. The recorded images were digitized and enhanced to assist in the identification of the vortex location. The vortex trajectories were compared with established data and with the paths generated by the general tip vortex path equations. It was found that these equations oversimplified the vortex trajectories, modelling neither the interaction between vortices nor their meandering. The wakes studied showed evidence of vortex interaction. It was found that vortices close to one another combined in pairs and spun about a common center as they moved downstream. A new mean path equation was thus defined which could model this type of behavior. An exponential equation was selected to model the mean path. To assist in the determination of the order which best suited the curve, the least squares method was used. The meandering of the vortex trajectory about its mean path was studied and the types of instability present were determined. Three types of instability were found in tip vortices; short-wave, mutual-inductance, and long-wave. It was discovered that the helical path followed by a hovering rotor's tip vortex was unstable under most flight conditions and that fluid damping suppressed the magnitude of these instabilities.

Quin, G. and Si, J.

"THE COMPREHENSIVE STUDY ON ADVANCED WINGTIP DEVICES IN LARGE CIVIL AIRCRAFT"

ICAS Paper 2012-8.8.3, September 2012, Brisbane, Australia.

Adding a wingtip device to wings of aircraft can reduce the induced drag, improve lift-drag ratio, and dissipate the strong wake vortex in aerodynamics, etc. However, the flutter characterization of the aircraft is changed simultaneously, and so is the structural weight. There are many researches on the drag reduction of wingtip devices all over the world, however, the flutter characterization of three kinds of advanced wingtip devices (blended, sharklet, ladder) is not studied fully, especially the overall performance from aerodynamic flutter and weight. So three kinds of advanced wingtip devices (blended, sharklet, ladder) are researched by using the numerical simulation method from aerodynamics, flutter and weight in this paper. Meanwhile, the effects of wingtip device height on aircraft's flutter is also investigated.

Quon, E. W., Smith, M. J., Whitehouse, G. R. and Wachspress, D. A.

"HIERARCHICAL VARIABLE FIDELITY METHODS FOR ROTORCRAFT AERODYNAMIC DESIGN AND ANALYSIS"

American Helicopter Society 67th Annual Forum, May 2011, Virginia Beach, VA.

A coupling framework has been developed for unstructured computational fluid dynamic (CFD) solvers to allow for simple activation of a variety of wake solvers. In addition, the interface has been parallelized and extended to support dynamic, overset meshes in rotating frames. Wake capture and performance calculations demonstrate the validity of the framework. Demonstration cases include an oscillating wing, the hovering Caradonna-Tung rotor and ROBIN rotor-fuselage interaction for multiple coupling variations between CHARM, VorTran-M, and FUN3D. These results illustrate that the hybrid methods can provide more accurate results with reduced grid sizes for various applications. The

modification of only one solver at each incremental level of analysis permits the user to identify the source of changes in solution results.

Raat, J.

"VORTEX DEVELOPMENT AND BREAKDOWN"

AIAA Paper No. 1975-0881, Hartford, CT, June 1975

A trailing vortex is assumed to consist of a thin axisymmetric viscous core embedded in an inviscid flow of uniform circulation and with axial velocity that may depend on the distance along the core. Self-similar solutions for axial velocity and circulation are presented for the special case of an external velocity inversely proportional to the core length. Integral solutions for uniform external flow fall into three different categories: (1) Wake-type vortex development, (2) Breakdown when the prescribed azimuthal energy conversion mechanism can no longer be satisfied, (3) Breakdown through core flow reversal. The effect of external pressure gradients on breakdown is exhibited.

Rabinovitch, J., Brion, V. and Blanquart, G.

"EFFECT OF A SPLITTER PLATE ON THE DYNAMICS OF A VORTEX PAIR"

AIAA Paper No. 2011-3894, June 2011, Honolulu, Hawaii.

An experimental and numerical study was performed to investigate the behavior of a counter-rotating vortex pair as well as a single vortex in the vicinity of a wall. A wind tunnel with two NACA0012 profiles mounted vertically with an optional splitter plate in the center and a 3D PIV system were used to experimentally study the interactions between two counter-rotating vortices, as well as the interactions between a vortex and a wall. Many fundamental differences were found between the two configurations, which promote the growth of the Crow instability in the two-vortex configuration, but not in the one vortex/wall configuration. The numerical results obtained re-enforced the experimental results, and emphasize the fundamental physical differences between the two configurations. While modeling a vortex wall system with an image vortex may give correct integral results for loads experienced by blades, this model does not accurately describe the downstream dynamics of the vortex system.

Rad, T., Schonhals, S. and Hecker, P.

"DYNAMIC SEPARATION MINIMA COUPLED WITH WAKE VORTEX PREDICTIONS IN DEPENDENT RUNWAY CONFIGURATIONS"

ICAS Paper 2012-10.4.2, September 2012, Brisbane, Australia.

Wake vortices are an issue affecting both capacity and safety of air traffic and therefore need to be dealt with by appropriate measures and procedures. Today, the only means to prevent wake vortex encounters is procedural separation which however is static and in many cases conservative. The

concept of dynamic separations using wake vortex predictions aims at optimizing the separation between consecutive aircraft based on the knowledge of the actual position and strength of the wake vortices. A concept for approach procedures has been developed that involves dynamical calculation of minimum safe distance, adaption of follower aircraft speed and the corresponding approach types. The concept, its implementation and simulation test results will be presented and it will be discussed how it can be applied to contribute to an optimized use of available capacity while maintaining and improving the safety level.

Rad, T., Schonhals, S. and Hecker, P.

"DYNAMIC SEPARATION MINIMA COUPLED WITH WAKE VORTEX PREDICTIONS IN DEPENDENT RUNWAY CONFIGURATIONS"

Proceedings Institution of Mechanical Engineers Part G: Journal of Aerospace Engineering, Vol. 228, No. 2, 2014, pp. 1450-1457.

Wake vortices are an issue affecting both capacity and safety of air traffic and therefore need to be dealt with by appropriate measures and procedures. Today, the only means to prevent wake vortex encounters is procedural separation which however is static and in many cases conservative. The concept of dynamic separations using wake vortex predictions aims at optimizing the separation between consecutive aircraft based on the knowledge of the actual position and strength of the wake vortices. A concept for approach procedures has been developed that involves dynamical calculation of minimum safe distance, adaption of follower aircraft speed and the corresponding approach types. The concept, its implementation and simulation test results will be presented and it will be discussed how it can be applied to contribute to an optimized use of available capacity while maintaining and improving the safety level.

Radcliff, T. D., Burggraf, O. R. and Conlisk, A. T.

"USE OF A DEFORMABLE CORE VORTEX MODEL IN PREDICTING VORTEX-SURFACE INTERACTIONS"

AIAA Paper No. 1999-0169, Reno, NV, January 1999

The direct collision of a vortex with a surface is an important problem because significant impulsive loads may be generated leading to premature fatigue. Experimental results for the impingement of a tip-vortex on a cylindrical airframe indicate that a strong suction peak forms on the top of the airframe that subsequently decreases within milliseconds of vortex-surface contact. Previous attempts to simulate the decrease in the suction peak have resulted in numerical error as the vortex vorticity overlaps the physical airframe in an unphysical manner on close approach. In this paper we present a vortex model that allows the vortex core to deform, preventing any vorticity overlap. Unlike our previous results, this model predicts the reversal in the suction peak without significant error.

Raddatz, J. and Pahlke, K.

"3D EULER CALCULATIONS OF MULTIBLADED ROTORS IN HOVER: INVESTIGATION OF THE WAKE CAPTURING PROPERTIES"

Aerodynamics and Aeroacoustics of Rotorcraft, AGARD-CP-552, August 1995, pp. 13-1 to 13-16.

The 3D flowfield of a hovering rotor is calculated solving the Euler equations. Performing a grid refinement study, it is demonstrated that an Euler method can capture the wake and vortices of a hovering rotor without any wake modeling. Accurate prediction of these rotational flow field phenomena needs fine grids with a high resolution in the complete region of the wake system. Additionally, high accuracy for the treatment of all numerical boundaries, which affect the vortex wake, is required. On the other hand, the investigations have shown that surface air loads are less affected by a more detailed resolution of the wake system. A second part of the study is concerned with wake capturing properties on block boundaries, especially on inner boundaries of overlapping grids. Overlapping grids are very attractive for the computation of a rotor in lifting forward flight or a rotor-body flowfield in hover. The effect of overlapping grids using the chimera technique is investigated comparing Euler solutions for a hovering rotor on a chimera grid system and on conventional single block and two block calculations. The chimera solution reproduces all flow features. The present implementation shows disadvantages concerning the detailed resolution of the wake system.

Rader, L. G. and Kane, J. B.

"INVESTIGATION OF FACTORS AFFECTING MINIMUM INTERVAL BETWEEN AIRCRAFT TAKEOFFS (MITO)"

TM 79-9.12/1, September 1979, Calspan Corp., Los Angeles, CA

The factors that affect MITO fall into two basic categories: (1) the aerodynamic factors that contribute to vortex generation and to the control of following aircraft, and (2) the propulsion factors that contribute to the generation of exhaust turbulence and combustion by-products. A literature and data search failed to turn up any information related to the propulsion factors and only limited data related to the aerodynamic factors. The best current source of data are the DOT studies on landing and takeoff intervals of commercial aircraft. Although DOT's objectives in conducting these studies are significantly different from SAC's objectives for alert aircraft, it is possible that the DOT data will provide a good initial understanding of the takeoff interval problem.

Radko, T.

"LONG-RANGE INTERACTION AND ELASTIC COLLISIONS OF ISOLATED VORTICES"

J. Fluid Mech., Vol. 610, 2008, pp. 285-310

This study explores the interaction of two nearly axisymmetric two-dimensional vortices using a combination of numerical simulations and analytical arguments. We consider isolated or 'shielded' eddies, characterized by zero net vorticity. The ability of such vortices to propagate and interact is associated with the small dipolar component that is introduced initially. Numerical contour dynamics experiments indicate that the interaction of shielded eddies takes one of two forms, depending on

their initial separation and on the relative orientation of their dipolar components. Eddies can influence each other by remotely modifying the dipolar moments of partner vortices, an effect manifested in a gentle deflection of their trajectories from a straight course. Strong interactions occur when eddies collide and rebound. The remote interaction is explained by weakly nonlinear theory in which the basic state consists of identical circularly symmetric eddies and the perturbation is assumed to be small. It is argued that the elastic rebounds observed during direct collisions are induced by the exchange of fluid between colliding vortices.

Raducanu, D., Nedelcu, I., Safta, D., Moldoveanu, C.-E. and Somoia, P.

"RESEARCH CONCERNING THE INTERACTION BETWEEN THE GROUND AND THE TURBULENT AIRCRAFT WAKE VORTEX"

Proceedings of the World Congress on Engineering , Vol. II, July 2009, London, UK.

The problem developed in this contribution is encountered in airplane aerodynamics and concerns the influence of long-life longitudinal wake vortices generated by wing tips or by external obstacles such as reactors or landing gears. At the edge of such obstacles, longitudinal vortices are created by pressure differences inside the boundary layers and rotate in opposite senses. The numerical simulation used for understanding the mechanisms were generally time evolution computation on a fixed space box with periodic boundary conditions using a transformation of the time evolution into a downstream evolution. The flow will be perturbed by prescribed disturbances or by a turbulent field.

Raffel, M.

"PIV MEASUREMENTS OF WAKE VORTICES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Over the past decade particle image velocimetry (PIV) has matured from its developmental stage to a reliable whole field flow measurement technique and now finds uses in a continuously broadening range of applications. An especially important field of PIV applications is the measurement of wake vortices in aeronautics. The application of the PIV technique has been demonstrated by various experimental investigations on wake vortices. Two experiments were performed in order to investigate details of the vortex formation from helicopter blade tips in a large wind tunnel. Furthermore, the wake measurements of a propeller, which have been performed in a smaller facility, and in addition to that, simultaneous measurements of the velocity and density fields were conducted in a transonic wind tunnel to characterize the structure of compressible vortices. These results will be presented together with further examples of wake vortex PIV measurements in aerodynamics.

Raffel, M., Heineck, J. T., Schairer, E., Leopold, F. and Kindler, K.

"BACKGROUND-ORIENTED SCHLIEREN IMAGING FOR FULL-SCALE AND IN-FLIGHT TESTING"

Journal of the American Helicopter Society, Vol. 59, 2014, pp. 012002-1 to 012002-9.

Background-oriented schlieren (BOS) methods suited for large-scale and in-flight testing are presented with special emphasis on the detection and tracing of blade tip vortices in situ. Retroreflective recording and photogrammetric epipolar analysis for the computation of the vortices' spatial coordinates in the wind tunnel are described. Feasibility and fidelity of reference-free BOS in conjunction with natural formation backgrounds and related evaluation methods are discussed, additionally, illustrating their simplicity and robustness. Results of successful image acquisition from a chaser aircraft are presented allowing vortex wakes to be identified at a wide range of flight attitudes, including complex maneuvers.

Raffel, M., Richard, H., Agocs, J., Otter, D., Mattner, H. and Gohmann, U.

"EXPERIMENTAL ASPECTS OF PIV APPLIED TO A BO 105 HELICOPTER IN HOVER-FLIGHT CONDITION"

Paper No. 1192, 4th International Symposium on Particle Image Velocimetry, Gottingen, Germany, September 2001.

PIV experiments have been performed to derive quantitative flow velocity data of the blade tip vortex of a helicopter at full-scale. Due to relatively rough outdoor conditions e.g. to the helicopter induced wind, the ambient light, the large observation distances and changing winds, the seeding illumination and recording of this type of flow was challenging. This paper describes technical aspects of the measurement and presents first results.

Raffel, M., Richard, H., Ehrenfried, K., Van der Wall, B., Burley, C., Beaumier, P., McAlister, K. and Pengel, K.

"RECORDING AND EVALUATION METHODS OF PIV INVESTIGATIONS ON A HELICOPTER ROTOR MODEL"

Experiments in Fluids, Vol. 36, 2004, pp. 146-156

Three-component particle image velocimetry measurements at moderate speeds and observation distances can now be accomplished on a routine basis. This article discusses the experiment performed on a 4 m-diameter model rotor in the 6-mx8-m open test section of the Large Low Speed Facility of the German-Dutch Wind Tunnels. More than half a terabyte of raw data was recorded at various positions on the advancing and retreating sides of the rotor to obtain detailed measurements of the trailing vortex in the frame of an international project. This paper addresses measuring techniques and possible sources of errors and presents a limited number of cases for the purpose of illustrating the solutions to numerous technical challenges relating to the acquisition and analysis of vortical flows.

Raffel, M., Richard, H., Ehrenfried, K., Van der Wall, B., Burley, C., Beaumier, P., McAlister, K. and Pengel, K.

"RECORDING AND EVALUATION METHODS OF PIV INVESTIGATIONS ON A HELICOPTER ROTOR MODEL"

Experimenta in Fluids, Vol. 40, 2006, p. 665.

In the original publication of this article, there are typographical errors in the first equation. Accordingly, a following sentence should be revised.

Raffel, M., Richard, H., Schneider, G., Klinge, F., Ehrenfried, K., Pengel, K. and Feenstra, G.

"RECORDING AND EVALUATION METHODS OF PIV INVESTIGATIONS ON A HELICOPTER ROTOR MODEL"

11th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 2002

Particle image velocimetry (PIV) experiments have been performed in order to derive quantitative flow velocity data of blade tip vortices of a large-scale helicopter model and during a three-week wind tunnel test. The helicopter rotor model used was a model of the MBB Bo 105 of the German aerospace establishment DLR in Braunschweig. The rotor consists of four hingeless blades with 0.121 m chord length, rectangular blade planform, and -8 degrees linear twist. The airfoil was a NACA 23012 with tabbed trailing edge. During the test, the model was mainly operated in descent flight conditions where blade vortex interaction dominates the noise emission. The rotor rotational frequency was 17.35 Hz leading to a tip speed of 218 m/s. The PIV system consisted of five digital cameras and three double pulse Nd: YAG lasers with 2x320mJ each, which were mounted onto a common traversing system to keep the distance between the cameras and the light sheet constant while scanning the rotor wake.

Raffel, M., Seelhorst, U. and Willert, C.

"VORTICAL FLOW STRUCTURES AT A HELICOPTER ROTOR MODEL MEASURED BY LDV AND PIV"

The Aeronautical Journal, Vol. 102, No. 1014, April 1998, pp. 221-227.

Flowfield measurements of the blade tip vortices from a rotating helicopter rotor model were performed by three component laser-Doppler velocimetry (3D-LDV) and conventional (two component) particle image velocimetry (PIV). In general, the results are in good correspondence, but also illustrate the different properties of both techniques: LDV offers the capability of three-component measurements, whereas PIV captures the unsteadiness of the flowfield.

Raffel, M., Tung, C., Richard, H., Yu, Y. and Meier, G. E. A.

"BACKGROUND ORIENTED STEREOSCOPIC SCHLIEREN (BOSS) FOR FULL-SCALE HELICOPTER VORTEX CHARACTERIZATION"

Proceedings of 9th International Symposium on Flow Visualization, Edinburgh, Scotland, August 2000, pp. 450-1 - 450-11

Application of a novel schlieren technique, referred as Background Oriented Schlieren (BOS), with two different helicopter tests are presented. Additionally, another extended method, called Reference-free Background Oriented Stereoscopic Schlieren (BOSS), and the differences between these two techniques will be discussed. Experimental studies have been carried out to investigate details of the vortex formation from blade tips of different helicopters, an Eurocopter BK117 and a large US utility helicopter. The background-oriented techniques appear to well complement other optical techniques like shadowgraphy or focusing schlieren methods and yield additional quantitative information. Furthermore, these techniques allow - in contrast to laser-based techniques - to study the effect of Reynolds numbers on vortex development from blade tips in full-scale flight tests more easily.

Rafi, M. and Steck, J. E.

"RESPONSE AND RECOVERY OF AN MRAC ADVANCED FLIGHT CONTROL SYSTEM TO WAKE VORTEX ENCOUNTERS"

AIAA Paper 2013-5209, August 2013, Boston, MA,

A three-dimensional, twin-core wake vortex model is developed within the MATLAB/Simulink environment, and the effects of this disturbance on a 6 Degree of Freedom general aviation-based MRAC flight control system is studied. An envelope protection scheme is developed to augment the aircraft's response to the disturbance, and three scenarios are tested to evaluate the controller's performance in response to and recovery from the wake vortex. These scenarios include the controller responding with no pilot input, the controller responding with pilot input, and the pilot responding with no controller input. Pilot-in-the-loop testing and simulation runs are performed, and it is found that having the controller active greatly improves response and recovery performance during and after the wake vortex encounter.

Ragab, S.

"DIRECT NUMERICAL SIMULATION OF INSTABILITY WAVES IN A TRAILING VORTEX"

AIAA Paper No. 1995-0591, Reno, NV, January 1995

Temporal direct numerical simulation is performed to study the nonlinear development of helical instability waves in a trailing vortex. The basic state is given by the q-vortex and the disturbance field is initialized by the helical mode. A sixth-order compact finite-difference method is used in the cross plane while Fourier series is used in the periodic axial direction. Contours of a passive scalar are used to study the entrainment process that redistributes angular and axial momentum between the core and its surroundings. Such a process leads to relaminarization of the core.

Ragab, S. A. and Sreedhar, M. K.

"LARGE SCALE STRUCTURES IN TRAILING VORTICES"

AIAA Paper No. 1994-2316, Colorado Springs, CO, June 1994

Large eddy simulation (LES) is performed to study the response of trailing vortices to random and controlled disturbances. The q-vortex (Batchelor 1964) is used as a model of such vortices. When the vortex is linearly unstable, the disturbances grow and result in the generation of large-scale helical structures. During the period of growth of the disturbance, the mean tangential velocity deficit weakens appreciably. This results in a stabilizing mean flow which quenches the large-scale motions, and the vortex returns to a laminar configuration.

Ragab, S. and Sreedhar, M.

"NUMERICAL SIMULATION OF VORTICES WITH AXIAL VELOCITY DEFICITS"

Phys. Fluids, Vol. 7, No. 3, March 1995, pp. 549-558

Axial velocity deficit is a source of instability in vortices that may otherwise be stable. Temporal large-eddy simulation is performed to study the response of vortices with axial velocity deficits to random and controlled disturbances at high Reynolds numbers. The q vortex is used as a model of such vortices. When the vortex is linearly unstable, the disturbances grow and result in the appearance of large-scale helical sheets of vorticity. Later, these large-scale helical structures break up into small-scale filaments. Associated with the formation of the large-scale structures is a redistribution of both angular and axial momentum between the core and the surroundings. The redistribution weakens the axial velocity deficit in the core while strengthens the rigid-body-like rotation of the core. The emerging mean velocity profiles drive the vortex core to a stable configuration. The vortex eventually returns to a laminar state, with an insignificant decay in the tangential velocity, but with a much-weakened axial velocity deficit. A direct numerical simulation obtained at a lower Reynolds number confirms the above conclusions.

Ragsdale, R. G.

"APPLICABILITY OF MIXING LENGTH THEORY TO A TURBULENT VORTEX SYSTEM"

NASA TN D-1051, August 1961, Lewis Research Center, Cleveland, OH

Techniques of mixing length theory established for pipe flow are used to develop analogous expressions for turbulent vortex flow; the ability of these functions to correlate vortex data is then evaluated. Experimentally measured tangential velocity and static-pressure profiles are used to determine turbulent Reynolds numbers from Navier-Stokes solutions for compressible flow in the annular region of a vortex with constant eddy viscosity assumed. Karman and Prandtl type mixing length expressions for vortex flow are given for various assumed boundary conditions. A modified Karman expression for eddy viscosity is derived and best correlates the data for the entire range of experimental conditions.

Rahm, S.

"RECENT AND ONGOING COHERENT DOPPLER LIDAR MEASUREMENTS AT DLR"

17th Coherent Laser Radar Conference, June 2013, Barcelona, Spain.

In the past the coherent Doppler Lidar of DLR was used both onboard the Falcon research aircraft and ground based in a 20 ft container. At the ground-based measurements mainly wake vortex of aircrafts were investigated but there was also one campaign with observations at a wind energy power plant. At airborne campaigns the 3-dimensional wind field was the main interest. However having a lidar available at sudden events like the Eyjafjallajökull eruption on Iceland has opened an opportunity for measurements where normally another Lidar with shorter pulse and depolarization channel would have been chosen if available in this moment. This paper will report about the following campaigns: (A) 2009, Wind energy Bremerhafen: Measurement of the flow before and after a wind power plant. (B) 2010, Eyjafjalla volcanic ash: This was an ad-hoc campaign to make some statement to volcanic ash content over Europe. (C) 2012, Wake vortex reference measurements Belgium: Here the DLR System was used as a 'reference' for a recently developed direct detection lidar. (D) 2013, Saltrac/Volcats: Current campaign at the Cape Verde Islands and Antigua in order to trace Sahara dust outbreaks.

Rahm, S. and Smalikho, I.

"AIRCRAFT WAKE VORTEX MEASUREMENT WITH AIRBORNE COHERENT DOPPLER LIDAR"

J. Aircraft, Vol. 45, No. 4, July-August 2008, pp. 1148-1155

An experiment for airborne Doppler lidar measurement of wake vortices generated by a large transport aircraft in the free atmosphere has been successfully carried out. In this paper, the description of the experiment, data processing procedure, and measurement results are given. It was shown using smoke generators placed on large transport aircraft wings allows some high-quality wake vortex measurements with 2 micron coherent Doppler lidar installed in a second aircraft.

Rahm, S., Smalikho, I. and Kopp, F.

"CHARACTERIZATION OF AIRCRAFT WAKE VORTICES BY AIRBORNE DOPPLER LIDAR"

Journal of Aircraft, Vol. 44, No. 3, May-June 2007, pp. 799-805

This paper presents a new method of wake-vortex characterization by using the 2-micron coherent Doppler lidar in airborne configuration. After modification of the scanning and data acquisition tools, the lidar system has been integrated in the DLR research aircraft Falcon 20. For wake-vortex generation a second DLR aircraft, the Advanced Technologies Testing Aircraft System equipped with a smoke generator on the portside wing, was used. Different scanning modes and flight strategies have been investigated and tested during three tryout flights. Results of vortex trajectories and circulation strengths, measured in the upper part of and above the atmospheric boundary layer, are presented. Based on the results of the tryout flights, the potential of this method for characterization of wake vortices from large transport aircraft equipped with smoke generators is estimated.

Raj, P. and Iversen, J. D.

"COMPUTATIONAL SIMULATION OF TURBULENT VORTEX MERGER AND DECAY"

AIAA Paper 1979-0278, January 1979, New Orleans, LA.

The interaction and eventual merger of corotational vortices and the decay of a single vortex have been studied by employing zero-, one-, and two-equation turbulent-flow models to gain a better understanding of the role of turbulence. An implicit finite-difference procedure is used to integrate the unsteady, two-dimensional equations in a cross-plane. The zero- and one-equation formulations utilize a mixing-length model, which incorporates the streamline curvature effect by prescribing a spatially-varying mixing-length. In the two-equation model, the turbulence kinetic energy equation and a modified rate of dissipation equation which includes a streamline curvature correction are solved. Computational results of different models applied to various flow-configurations are presented and compared with available experimental data whenever possible.

Raj, P. and Iversen, J. D.

"COMPUTATIONAL SIMULATION OF TURBULENT VORTEX MERGER AND DECAY"

AIAA Journal, Vol. 18, No. 8, August 1980, pp. 865-866

In recent years, many theoretical and experimental studies have been conducted to gain a better understanding of corotational vortex merger in connection with the pairing of organized vortex structures observed in mixing layers and with the attenuation of wake-vortex hazard associated with wide-body aircraft. The latter is accomplished by modifying the wing such that two or more corotating vortices are shed from each half-span. The merger of these vortices can result in a redistribution of vorticity such that the hazard to trailing aircraft is considerably reduced compared to the conventional wing. In the present investigation, the interaction and merger of corotational vortices and the decay of a single vortex have been studied by employing zero-, one-, and two-equation turbulent flow models to bridge the gap between the theoretical models and experimental observations. The zero- and one-equation formulations utilize a mixing-length model which incorporates the streamline curvature effect by prescribing a particular spatial variation. In the two-equation model, a turbulence kinetic energy equation and a rate of dissipation equation modified to include streamline curvature correction are solved. The computed results corresponding to the different flow models are compared with the available experimental data.

Raj, P. and Iversen, J. D.

"COMPUTATIONAL STUDIES OF TURBULENT MERGER OF COROTATIONAL VORTICES"

AIAA Paper No. 1978-0108, Huntsville, AL, January 1978

A computational study has been conducted to gain a better understanding of the criteria governing the merger of corotating vortices. The zero-equation and one-equation turbulent-flow models are used to model the interaction of two rolled-up, corotational vortices. A model appropriate for the swirling

flow under consideration has been proposed to prescribe the algebraic variation of mixing-length in the flow field. The unsteady, two-dimensional equations in a cross-plane are solved for primitive variables using an implicit finite-difference code. The computed downstream merging distances are in good agreement with available wind tunnel data.

Raj, P. and Iversen, J. D.

"INVISCID INTERACTION OF TRAILING VORTEX SHEETS APPROXIMATED BY POINT VORTICES"

J. Aircraft, Vol. 15, No. 12, December 1978, pp. 857-859

A computational study of the mutual interaction of vorticity sheets shed behind wings kept at a small distance apart has been made. The sheets are modeled by arrays of discrete point vortices and their inviscid motion is computed. The gross features exhibited by the results confirm the experimental observation that for a small initial separation distance, the trailing vorticity sheets roll up together.

Raju, S. P. G., Nigam, A. and Verghese, M. P.

"DEVELOPMENT OF A VORTICITY METER"

Journal of Aircraft, Vol. 15, No. 11, November 1978, pp. 799-800.

A vorticity meter which is simple to construct and reliable in operation has been designed and fabricated. It has been shown that correction to the measured rotor speed arising due to bearing friction obeys a simple law and can be easily derived by using two shaft (and bearing) sizes in sequence in the same instrument. Errors arising due to the inclination of the flow to the axis of the instrument have been shown to be insignificant for inclinations of the order of 5 degrees. The instrument is expected to be useful in studying flows with vorticity, such as trailing vortices.

Ramachandran, K., Steinhoff, J. and Yonghu, W.

"FREE-WAKE COMPUTATION OF HELICOPTER ROTOR FLOWFIELD FOR GENERAL FLIGHT REGIME"

Report ARO 25623.4-EG-S, March 1993, Flow Analysis Inc., Brooklyn, NY.

A CFD based computer code, HELIX II, has been developed for computing helicopter rotor flowfield in hover and in forward flight. In order to predict the vibratory airloads in forward flight and the performance in hover the effect of shed wake must be accurately accounted for. This has been accomplished by an unique vorticity embedding procedure. The wake is convected in a Lagrangian sense and does not suffer from numerical dissipation. The effect of this convected wake is included in the Eulerian using Clebach representation. The unsteady full potential equation is solved in the Eulerian grid with the embedded vortical velocity accounting for the influence of wake. The wake evolves as a part of the solution. Dynamic grid modifications are performed at each time step to account for blade motion and deformation. These modifications are confined to regions near the blade using suitable blending functions. In addition, a vorticity confinement method is developed which involves adding a

term to the momentum conservation equation of fluid dynamics. This modification is very useful in the numerical solution of flow problems involving vortical regions. The Euler equations solved with this extra term can convect vortices without numerical dissipation.

Ramaprian, B. R.

"INTERACTIONS OF SPANWISE AND CHORDWISE VORTICITY ASSOCIATED WITH THREE-DIMENSIONAL DYNAMIC STALL OVER AN OSCILLATING WING"

US Army Research Office Report, Oct. 1994, Washington State Univ., Pullman, WA.

The research work involved the measurement of the pressure and velocity fields in the three-dimensional flow field surrounding and in the wake of the tip region of a rectangular wing of NACA 0015 profile. Measurements were made both with the wing stationary and with the wing oscillating sinusoidally in pitch about its quarter-chord axis. Pressure transducers and three-component laser Doppler velocimetry were used in these measurements. The results have been used to understand the vorticity dynamics in three-dimensional steady and unsteady flows. The study is relevant to helicopter rotor aerodynamics.

Ramaprian, B. R. and Zheng, Y.

"NEAR FIELD OF THE TIP VORTEX BEHIND AN OSCILLATING RECTANGULAR WING"

AIAA Journal, Vol. 36, No. 7, July 1998, pp. 1263-1269

Data on the evolution of the unsteady three-dimensional tip vortex in the near wake (0-3 chord lengths behind the wing) of a rectangular NACA 0015 wing oscillating sinusoidally in pitch about its quarter-chord axis are presented. These data were obtained using three-component laser Doppler velocimetry (LDV). The experiments were performed in a low-speed wind tunnel at a Reynolds number of 180,000. The wing had a semi aspect ratio of 2. It was oscillated at a frequency of 1 Hz and an amplitude of 5 deg around a mean incidence of 10 deg. The instantaneous LDV data were used to obtain information on the distribution of phase-locked velocity and vorticity components across the vortex, as well as the phase-locked circulation associated with the evolving vortex. The data indicate that the average trajectory of the oscillating vortex in the near field is very nearly the same as for a stationary wing at the mean incidence. The length and circulation scales, as well as the maximum circulation carried by the vortex flow under the conditions studied, are modulated in a significantly nonquasisteady manner. Nevertheless, beyond about 0.7 chord length, the normalized circulation distribution across most of the inner part of the vortex exhibits, at all times, the same universal behavior as the vortex behind a stationary wing.

Ramaprian, B. R. and Zheng, Y.

"MEASUREMENTS IN ROLLUP REGION OF THE TIP VORTEX FROM A RECTANGULAR WING"

AIAA Journal, Vol. 35, No. 12, December 1997, pp. 1837-1843

The evolving three-dimensional flowfield of the tip vortex in the near wake of a rectangular wing at incidence was studied in detail, using three-component laser Doppler velocimetry. The flow quantities measured were the three components of the instantaneous velocity. These data were used to obtain the distributions of velocity, vorticity, and circulation across the vortex at several axial locations in the flow for several angles of incidence. The data have been used to understand the process of rollup of the shear layer into the vortex in the near wake, as well as its kinematic structure. The data indicate that the rollup takes place quite quickly and the inner part of the three-dimensional vortex becomes nearly axisymmetric within about two chord lengths downstream of the trailing edge. Even though the vortex behavior in the near wake is, in general, strongly dependent on the initial conditions, the vortex trajectory appears to be described reasonably well by the overall wing lift and the freestream velocity. Also, even in the near wake, circumferentially averaged mean flow properties in the inner part of the nearly axisymmetric vortex begin to exhibit a universal structure characteristic of conceptual asymptotic trailing vortices.

Ramasamy, M. and Leishman, J. G.

"REYNOLDS NUMBER BASED BLADE TIP VORTEX MODEL"

61st Annual Forum and Technology Display, American Helicopter Society International, Grapevine, TX, June 2005

A mathematical model has been developed to estimate the temporal growth properties of helicopter blade tip vortices at any vortex Reynolds number. One unique feature of the model is that it takes into account rotational stratification (Richardson's number) effects on the distribution of turbulent viscosity inside the tip vortices. This model is combined with another model for the effects of filament stretching in predicting the temporal evolution of the vortex. A turbulent growth model solves exactly for the tangential (swirl) velocity starting from the Navier-Stokes equations using an assumed variation in eddy viscosity across the vortex core. This variation is a function of the local Richardson's number, and the final solution becomes dependent on vortex Reynolds number. A more parsimonious functional approximation is given to represent the induced velocity distribution in the tip vortices for practical applications. It is shown that the temporal core growth rate predicted by the new model increases with an increase in vortex Reynolds number, which is consistent with experimental observations. The predictions from the model were validated, wherever possible, with tip vortex measurements from both model- and full-scale rotors.

Ramasamy, M. and Leishman, J. G.

"PHASED-LOCKED PARTICLE IMAGE VELOCIMETRY MEASUREMENTS OF A FLAPPING WING"

Journal of Aircraft, Vol. 43, No. 6, November-December 2006, pp. 1867-1875.

The unsteady aerodynamics of a biomimetic inspired flapping-wing mechanism has been analyzed by performing detailed phase-locked diagnostics of its flow field. Flow visualization and particle image velocimetry results have shown the presence of a shed dynamic stall vortex that spans across most of the wing span. The shedding of this type of leading-edge vortex was accompanied by the formation of another leading-edge vortex before the first vortex reached the midchord, resulting in multiple shedding leading-edge vortices on the top surface of the wing during each wing stroke. A strong starting vortex was also formed at the trailing edge of the wing during the early part of its translational stroke. This vortex continuously gained strength from shed vorticity as the wing accelerated into its stroke. The starting vortex remained close to the trailing edge until the wing reached midstroke. A pair of vortices that continuously trailed from the root and tip of the wing were identified, both of which induced a significant downwash velocity over the wing surface. These trailed vortices were found to exhibit a contracting wake structure as they convected into the wake before the wing, consistent with an increase in slipstream velocity. The evolution of the tip and root vortex pair showed rapid diffusive characteristics with an increase in time (wake age)..

Ramasamy, M. and Leishman, J. G.

"BENCHMARKING PARTICLE IMAGE VELOCIMETRY WITH LASER DOPPLER VELOCIMETRY FOR ROTOR WAKE MEASUREMENTS"

AIAA Journal, Vol. 45, No. 11, November 2007, pp. 2622-2633

An experiment was conducted to identify and measure the sources of uncertainty that are associated with the application of particle image velocimetry to the measurement of the vortical wakes trailing from helicopter rotor blades. Phase-resolved, three-component particle image velocimetry measurements were performed in the wake of a subscale rotor operating in hover, and were compared with high-resolution three-component laser Doppler velocimetry measurements obtained with the same rotor under identical operating conditions. This helped formulate the essential experimental conditions that need to be satisfied for particle image velocimetry to accurately resolve the high-velocity gradient, high streamline curvature flows that are present inside the rotor wake and in the blade tip vortices. Uncertainties associated with the calibration, acquisition, and processing of the particle image velocimetry images were analyzed in detail. It was shown that the optimization of laser pulse separation time is fundamental to reduce the errors associated with acceleration and curvature effects. Similarly, the interrogation window size was shown to play a critical role in determining the velocity gradient bias errors. The correlation between the laser Doppler velocimetry and particle image velocimetry measurements of the tip vortex characteristics, such as core radius and peak swirl velocity, were found to be excellent.

Ramasamy, M. and Leishman, J. G.

"INTERDEPENDENCE OF DIFFUSION AND STRAINING OF HELICOPTER BLADE TIP VORTICES"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1014-1024

An experiment was performed to help quantify the interdependence of viscous/turbulent diffusion and straining effects on the development of helicopter rotor tip vortices. The properties of the blade tip vortices were measured in the wake of a small-scale hovering rotor and compared to the results for the case when the wake approached a solid boundary. The presence of the boundary created velocity gradients that forced the tip vortex filaments to strain, allowing the effects of this process on the vortices to be measured relative to the baseline case without the boundary. It is shown that vortex stretching begins to decrease the viscous core size, and when the strain rates become large, this can balance the normal growth in the vortex core resulting from diffusion. The present results were used to help develop a more general tip vortex model suitable for use in a variety of helicopter rotor aero acoustic applications. The proposed engineering model combines the effects of turbulent diffusion and strain on the vortex core growth. The empirical coefficients of this model have been derived based on the best available results from rotating-wing tip vortex measurements.

Ramasamy, M., Gold, N. P. and Bhagwat, M. J.

"FLOWFIELD MEASUREMENTS TO UNDERSTAND EFFECTS OF WAKE BEHAVIOR ON ROTOR PERFORMANCE"

AIAA Paper No. 2010-4237, June-July 2010, Chicago, Illinois.

The effect of large twist on hovering rotor performance was investigated using detailed flowfield measurements. The experiments were conducted using a three-bladed model-scale rotor with two different sets of blades. One employed simple rectangular untwisted blades while the other used scaled-down XV-15 tilt-rotor blades, with a large non-linear twist. The highly-twisted blades were expected to give better hover performance at high thrust coefficients. However, the model scale rotor could not be operated at sufficiently high thrust because of early onset of blade stall at the low Reynolds numbers. At lower thrusts, the untwisted blades showed somewhat better performance than the highly-twisted blades. Nevertheless, the flowfield measurements showed some key wake differences between the two rotors. These observations together with simple blade element momentum theory (also called annular disk momentum theory) helped understand the rotor performance.

Ramasamy, M., Lee, T. E. and Leishman, J. G.

"FLOWFIELD OF A ROTATING-WING MICRO AIR VEHICLE"

Journal of Aircraft, Vol. 44, No. 4, July-August 2007, pp. 1236-1244.

Experiments were conducted to measure the performance of a rotor, typical of that used on a rotating-wing micro air vehicle, which was shown to develop relatively low hovering efficiency. This inefficiency can be traced to high profile drag losses on the blades and to the relatively large turbulent and rotational aerodynamic losses that are associated with the structure of the rotor wake. High-resolution flow visualization images have divulged several interesting flow features that appear unique

to rotors operating at low Reynolds numbers. The wake sheets trailing from the rotor blades were found to be much thicker and more turbulent than their higher chord Reynolds number counterparts. Similarly, the viscous core sizes of the tip vortices were relatively large as a fraction of blade chord. However, the flows in the tip vortices themselves were found to be similar, with laminar flow near their core axis and an outer turbulent region. Particle image velocimetry measurements were made to quantify the structure and strength of the wake flow, including the tip vortices. An analysis of the vortex aging process was conducted. A new nondimensional equivalent time scaling parameter is proposed to normalize the rate of growth of the vortex cores that are generated at substantially different vortex Reynolds numbers.

Ramasamy, M., Paetzel, R. and Bhagwat, M. J.

"APERIODICITY CORRECTION FOR ROTOR TIP VORTEX MEASUREMENTS"

67th AHS Annual Forum, May 2011, Virginia Beach, VA.

The initial roll-up of a tip vortex trailing from a model-scale, hovering rotor was measured using particle image velocimetry. The unique feature of the measurements was that a microscope was attached to the camera to allow much higher spatial resolution than hitherto possible. This also posed some unique challenges. In particular, the existing methodologies to correct for aperiodicity in the tip vortex locations could not be easily extended to the present measurements. The difficulty stemmed from the inability to accurately determine the vortex center, which is a prerequisite for the correction procedure. A new method is proposed for determining the vortex center, as well as the vortex core properties, using a least-squares fit approach. This approach has the obvious advantage that the properties are derived from not just a few points near the vortex core, but from a much larger area of flow measurements. Results clearly demonstrate the advantage in the form of reduced variation in the estimated core properties, and the self-consistent results obtained using three different aperiodicity correction methods.

Ramirez, Jr., A., Rao, B. M. and Cronk, A. E.

"LONGITUDINAL RESPONSE OF AN AIRCRAFT DUE TO A TRAILING VORTEX PAIR"

J. Aircraft, Vol. 10, No. 10, October 1973, pp. 638-639

An approximate method to predict the response of a small aircraft in longitudinal motion when it is flying through a trailing vortex of a large aircraft was developed. The longitudinal stability equations of motion were linearized. The loads were computed assuming the wing and the horizontal tail as the lifting surfaces and neglecting the wing-body-tail interference effects. The results of the lift and moment coefficients variations with respect to the distance between the test aircraft, and time histories of the flight variables u -bar, α , and θ were shown.

Ramsey, D. and Nguyen, C.

"SIMULATING WAKE VORTEX DETECTION WITH THE SENSIVU DOPPLER WIND LIDAR SIMULATOR"

NASA/CR-2014-218276, January 2014, Aerospace Innovations, Yorktown, VA.

In support of NASA's Atmospheric Environment Safety Technologies NRA research topic on Wake Vortex Hazard Investigation, Aerospace Innovations (AI) investigated a set of techniques for detecting wake vortex hazards from arbitrary viewing angles, including axial perspectives. This technical report describes an approach to this problem and presents results from its implementation in a virtual lidar simulator developed at AI. Three-dimensional data volumes from NASA's Terminal Area Simulation System (TASS) containing strong turbulent vortices were used as the atmospheric domain for these studies, in addition to an analytical vortex model in 3-D space. By incorporating a third-party radiative transfer code (BACKSCAT 4), user-defined aerosol layers can be incorporated into atmospheric models, simulating attenuation and backscatter in different environmental conditions and altitudes. A hazard detection algorithm is described that uses a two-component spectral model to identify vortex signatures observable from arbitrary angles.

Ramsey, D. J. and Chi Nguyen, D. P.

"CHARACTERIZING AIRCRAFT WAKE VORTICES WITH GROUND-BASED PULSED COHERENT LIDAR: EFFECTS OF VORTEX CIRCULATION STRENGTH AND LIDAR SIGNAL-TO-NOISE RATIO ON THE SPECTRAL SIGNATURE"

AIAA Paper 2011-3198, June 2011, Honolulu, Hawaii.

The pulsed coherent lidar is a well-known instrument for detecting and characterizing transverse cross-sections of aircraft wake vortices. One class of algorithms uses spectral 'maximum velocities' to estimate vortex parameters, and these velocities are dependent upon several factors described in this paper. A lidar simulator, developed by Lockheed Martin Coherent Technologies, was used to investigate these factors and explore their qualitative effects on the spectral signature. An algorithm is briefly described which attempts to manage these effects, and examples are shown of vortex tracks resulting from processing simulated and field-measured lidar data.

Ramsey, V. W.

"ACOUSTIC SCATTERING FROM AN AIRCRAFT TRAILING VORTEX"

Ph.D. Thesis, May 1974, Stanford Univ., Palo Alto, CA

A detailed analysis is presented of acoustic scattering from the velocity field of an aircraft trailing vortex. A model of a turbulent vortex is obtained from the aerodynamic literature. Published vortex theories and experimental data are used to evaluate vortex flow compressibility, turbulence level versus that of the environment, the existence of an inertial subrange, and vortex turbulence scales. Much of this information then provides a basis for discussing refraction, multiple scattering, and the validity of the Born approximation in aircraft vortices.

Ramsey, V. W. and Peterson, A. M.

"ACOUSTIC SCATTERING FROM A TURBULENT VORTEX"

NASA-CR-141186, January 1974, Stanford University Electronics Labs., Palo Alto, CA

With the aid of the Born approximation, the time autocorrelation and power spectral density are calculated for the received acoustic signal scattered from velocity fluctuations in a turbulent aircraft trailing vortex. The turbulence is required to be globally stationary, but only locally homogeneous. The treatment includes the effects of spectral broadening due to convection of the scattering eddies by a spatially varying mean flow and by macro eddies. The 3 dB bandwidth of the received signal is related to the scattering angle and the core Mach number of the vortex. A primary feature of the analysis is that it provides a method for inferring the radial intensity distribution of turbulence in a vortex. The analysis technique is also applicable to scattering from other turbulent flows where significant variations of turbulence level occur over distances on the order of the macro eddy size.

Ramsey, W. and Milgram, J.

"COMPUTATION METHOD FOR FORCES ON AIRCRAFT IN CLOSE PROXIMITY"

Aerotecnica Missili e Spazio, Vol. 76, Nos. 3-4, July-December 1997, pp. 93-100.

Numerical modeling of the unsteady aerodynamics of aircraft in proximity is important for quantifying the wake-vortex hazard on following aircraft. Issues include unsteady motions and the structural loads due to the unsteady force. This paper presents a method for computing unsteady loads and wake trajectories as one aircraft passes through the wake of another. The method is based on recent extensions of unsteady vortex lattice theory which use desingularization techniques to reduce numerical instabilities associated with discretized vortex sheets. Results are presented showing the method to be relatively insensitive to the discretization of the aircraft. Several cases are analyzed, demonstrating the effect of wake roll-up, vertical displacement, and incidence angle on the force and moment time histories of the following aircraft.

Ran, H.

"NUMERICAL STUDY OF THE DYNAMICS AND SOUND GENERATION OF A TURBULENT VORTEX RING"

Ph.D. Thesis, June 2004, California Institute of Technology, Pasadena, CA

In the present study, Direct Numerical Simulations (DNS) of the fully compressible, three-dimensional Navier-Stokes equations are used to generate an axisymmetric vortex ring to which three-dimensional stochastic disturbances are added. The radiated acoustic field is computed directly in the near field, and by solving the wave equation in a spherical coordinate system in the far field. At high Reynolds number, a vortex ring will undergo an instability to azimuthal waves. The instability produces higher azimuthal modes and induces nonlinear interaction between the modes, and will cause the vortex ring to break down and transition to turbulence. The early stages of the simulation agree well with the linear instability theory. Nonlinear stage of instability, transition, formation of axial flow and

streamwise vorticity are analyzed and compared with experimental results. After turbulent transition, the evolution of statistical quantities becomes independent of viscosity and the initial geometry, and the flow become self-similar. The temporal evolution of quantities including total circulation, axial velocity profile, vortex ring displacement and vorticity profile agrees well with the self-similarity law. Turbulent energy spectrum, Reynolds stresses and turbulence production are also presented.

Ran, H. and Colonius, T.

"NUMERICAL SIMULATION OF SOUND RADIATED FROM A TURBULENT VORTEX RING"

AIAA Paper No. 2004-2918, Manchester, UK, May 2004

The acoustic field radiated by a turbulent vortex ring is studied. Direct Numerical Simulations (DNS) of the fully compressible, three-dimensional Navier-Stokes equations are used to generate an axisymmetric vortex ring to which 3D stochastic disturbances are added. The disturbances cause instability and turbulent transition of the vortex ring. Detailed information about temporal evolution of sound pressure level, spectrum and directivity associated with each mode is investigated. The peak frequency agrees well with experiments, and the directivity of each azimuthal mode agrees well with predictions of vortex sound theory. Based on the self-similar decay of the turbulent near field, the self-similar decay of the sound field is investigated. We also explore the connections with jet noise by modeling the jet as a de-correlated train of vortex rings.

Ran, H. and Colonius, T.

"NUMERICAL SIMULATION OF THE SOUND RADIATED BY A TURBULENT VORTEX RING"

Aeroacoustics, Vol. 8, No. 4, 2009, pp. 317-336.

The acoustic field radiated by a turbulent vortex ring is studied. Direct Numerical Simulations (DNS) of the fully compressible, three-dimensional Navier-Stokes equations are used to generate an axisymmetric vortex ring to which 3D stochastic disturbances are added. The disturbances cause instability and turbulent transition of the vortex ring. Detailed information about temporal evolution of sound pressure level, spectrum and directivity associated with modes of oscillation and their turbulent breakdown are investigated. The peak frequency agrees well with experiments, and the modal directivities agree well with predictions of vortex sound theory. Based on the self-similar decay of the turbulent near field, the self-similar decay of the sound field is investigated. We also explore the connections with jet noise by modeling the jet as a de-correlated train of vortex rings.

Randall, J. D. and Leibovich, S.

"THE CRITICAL STATE - A TRAPPED WAVE MODEL OF VORTEX BREAKDOWN"

J. Fluid Mech., Vol. 58, No. 3, May 1973, pp. 495-515

1765

A model of vortex breakdown is presented and its predictions compared with the experiments of Sarpkaya. The model is centered about a theory of long, weakly nonlinear waves propagating on critical flows in tubes of variable cross-section. Although the weakly nonlinear theory must be extended beyond its domain of formal validity, many of the experimentally observed features of vortex breakdown are reproduced by the model. The description of the time evolution of the flow field that is presented requires numerical calculations that are not simple, but some important conclusions may be determined by easy computations. In particular, the axial position of a breakdown may be found from a very simple equation.

Ranjan, P. and Ansell, P. J.

"COMPUTATIONAL ANALYSIS OF VORTEX WAKES WITHOUT NEAR-FIELD ROLLUP CHARACTERISTICS"

Journal of Aircraft, Vol. 55, No. 5, September-October 2018, pp. 2008-2021.

A computational study on the wake characteristics of span-optimized wings is discussed, where the effect of the wing span load on the resulting wake rollup characteristics and structure is emphasized. Two wing configurations, each optimized for minimum induced drag at a fixed $C_{sub L}$ and fixed bending-moment constraint, are studied; and their wake characteristics are compared against an elliptically loaded wing. Results from Navier-Stokes simulations across the near-field wake demonstrate a symmetric large-scale rotation of the entire wake structure, centered roughly at the quarter-span location, for the bending-optimized wings. This wake structure is contrasted with the classical tip vortex formation associated with the elliptic span load, which occurs immediately in the wing near-field wake. The far-wake structure was also studied using a free-wake simulation approach. The results from this analysis indicate a gradual rollup of the entire wake far downstream for the bending-optimized wings. This absence of wake rollup in the near field is envisaged as a potential means to reduce vortex interactions with downstream surfaces of aircraft and prevent other adverse operational challenges associated with wingtip vortices.

Rankenburg, J.

"THE WAKE VORTICES WARNING SYSTEM (WVWS) FOR FRANKFURT AIRPORT PARALLEL RUNWAY SYSTEM 25"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206233, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 537-548

The WVWS objective is to reduce/suspend increased wake vortex separation minima between staggered aircraft on final approach to the two parallel runways 25 at Frankfurt airport to increase arrival capacity whilst maintaining or increasing safety. Aircraft approaching the same runway will continue to be separated according to the increased (ICAO) wake vortex separation minima. Issues and analysis supporting this objective are presented.

Rasch, N. and Walaconis, J.

"AIRCRAFT JET-BLAST EFFECTS AT INTERSECTION OF RUNWAYS 31L-4R, JOHN F. KENNEDY INTERNATIONAL AIRPORT"

Technical Letter Report NA-77-70-LR, December 1977, FAA National Aviation Facilities Experimental Center, Atlantic City, NJ.

This project was performed in response to a letter request from the Eastern Region, AEA-1, requiring additional studies be conducted at John F. Kennedy International Airport to facilitate the determination of the minimum distance from the jet blast fence that a takeoff may commence on Runway 31L without causing interference to aircraft landing simultaneously on Runway 4R. The study was completed and velocity envelopes were developed for each class aircraft for use in establishing minimum distance from the fence that takeoff rolls could commence to permit simultaneous operations.

Rath, C. B.

"WING TIP VORTEX STAGNATION PRESSURE SURVEY OF VARIOUS TIP SHAPES"

MS Thesis, August 1991, University of Texas, Arlington, TX.

The effects of wing tip shape on the tip vortex were studied experimentally under flow conditions typical of helicopter rotor tip operation ($M = 0.75$ and 0.78 , with $Re = 3,200,000$ and $5,600,000$). Four planforms were tested; rectangular, swept, tapered, and swept-tapered. Vortex stagnation pressure surveys were conducted at 1, 3 and 6 chords downstream of the tip. This yielded qualitative results in the initial roll-up region. Comparisons were made of the effects of Mach number, Reynolds number, downstream distance and tip shape on the vortex size, shape, location and minimum stagnation pressure ratio. The effects of tip shape were quite significant. The swept and swept-tapered tips produced larger, more diffuse vortices than the rectangular or tapered tips.

Rauleder, J. and Leishman, J. G.

"INTERACTIONS OF A VORTICAL FLOW WITH DISPERSED PARTICLES BELOW A ROTOR"

AIAA Journal, Vol. 54, No. 11, November 2016, pp. 3361-3373.

Measurements were made of the vortically dominated flow produced by a rotor hovering in ground effect over a mobile sediment bed. Time-resolved particle image velocimetry and particle tracking velocimetry were used to measure the two-phase flow as the rotor wake interacted with the bed. Mobilized sediment particles were tracked, with the objective to relate the particle motion to individual vortical structures and turbulent motions of the fluid. Although the tip vortices trailed from the rotor blades were the dominant flow features, secondary flow structures and organized turbulent motions were identified to affect the process of particle uplift. A vortex-induced secondary vortical structure convected downstream in between two consecutive blade tip vortices, and in a dynamic interplay with the tip vortices was shown to contribute to the uplift process of particles from the bed. Most tip vortices trailed a region of negative streamwise velocity fluctuations, which decelerated the particles

that could subsequently be picked up by a succeeding tip vortex. A quadrant analysis showed the preferential distribution of turbulence that could be correlated to sediment mobilization and uplift. Positive wall-normal velocity fluctuations (ejection and outward interaction events) were induced primarily by the tip vortices and correlated with the uplift of particles from the bed and their subsequent suspension.

Rautenberg, A., Allgeier, J., Jung, S. and Bange J.

"CALIBRATION PROCEDURE AND ACCURACY OF WIND AND TURBULENCE MEASUREMENTS WITH FIVE-HOLE PROBES ON FIXED-WING UNMANNED AIRCRAFT IN THE ATMOSPHERIC BOUNDARY LAYER AND WIND TURBINE WAKES"

Atmosphere, Vol. 124, No. 10, March 2019.

For research in the atmospheric boundary layer and in the vicinity of wind turbines, the turbulent 3D wind vector can be measured from fixed-wing unmanned aerial systems (UAS) with a five-hole probe and an inertial navigation system. Since non-zero vertical wind and varying horizontal wind causes variations in the airspeed of the UAS, and since it is desirable to sample with a flexible cruising airspeed to match a broad range of operational requirements, the influence of airspeed variations on mean values and turbulence statistics is investigated. Three calibrations of the five-hole probe at three different airspeeds are applied to the data of three flight experiments. Mean values and statistical moments of second order, calculated from horizontal straight level flights are compared between flights in a stably stratified polar boundary layer and flights over complex terrain in high turbulence. Mean values are robust against airspeed variations, but the turbulent kinetic energy, variances and especially covariances, and the integral length scale are strongly influenced. Furthermore, a transect through the wake of a wind turbine and a tip vortex is analyzed, showing the instantaneous influence of the intense variations of the airspeed on the measurement of the turbulent 3D wind vector. For turbulence statistics, flux calculations, and quantitative analysis of turbine wake characteristics, an independent measurement of the true airspeed with a pitot tube and the interpolation of calibration polynomials at different Reynolds numbers of the probe's tip onto the Reynolds number during the measurement, reducing the uncertainty significantly.

Rayleigh, L.

"ON THE DYNAMICS OF REVOLVING FLUIDS"

Proceedings Royal Soc. London, Series A, Vol. 93, 1916, pp. 148-154

So much of meteorology depends ultimately upon the dynamics of revolving fluid that is desirable to formulate as clearly as possible such simple conclusions as are within our reach, in the hope that they may assist our judgment when an exact analysis seems impracticable.

Rayner, J. M.

"DYNAMICS OF THE VORTEX WAKES OF FLYING AND SWIMMING VERTEBRATES"

Symposia of the Society for Experimental Biology, Vol. 49, 1995, pp. 131-155.

The vortex wakes of flying and swimming animals provide evidence of the history of aero- and hydrodynamic force generation during the locomotor cycle. Vortex-induced momentum flux in the wake is the reaction of forces the animal imposes on its environment, which must be in equilibrium with inertial and external forces. In flying birds and bats, the flapping wings generate lift both to provide thrust and to support the weight. Distinct wingbeat and wake movement patterns can be identified as gaits. In flow visualization experiments, only two wake patterns have been identified: a vortex ring gait with inactive upstroke, and a continuous vortex gait with active upstroke. These gaits may be modeled theoretically by free vortex and lifting line theory to predict mechanical energy consumption, aerodynamic forces, and muscle activity. Longer-winged birds undergo a distinct gait change with speed, but shorter-winged species use the vortex ring gait at all speeds. In swimming fish, the situation is more complex: the wake vortices form a reversed von Karman vortex sheet, but little is known about the mechanism of generation of the wake, or about how it varies with speed and acceleration or with body form and swimming mode. An unresolved complicating factor is the interaction between the drag wake of the flapping fish body and the thrusting wake from the tail.

Rayner, J. M. V.

"A VORTEX THEORY OF ANIMAL FLIGHT. PART 2. THE FORWARD FLIGHT OF BIRDS"

Journal of Fluid Mechanics, Vol. 91, part 4, 1979, pp. 731-763.

The vortex wake of a bird in steady forward flight is modelled by a chain of elliptical vortex rings, each generated by a single downstroke. The shape and inclination of each ring are determined by the downstroke geometry, and the size of each ring by the wing circulation; the momentum of the ring must overcome parasitic and profile drags and the bird's weight for the duration of a stroke period. From the equation of motion, it is possible to determine exactly the kinematics of the wing-stroke for any flight velocity. This approach agrees more readily with the nature of the wing stroke than the classical actuator disk and momentum-jet theory; it also dispenses with lift and induced drag coefficients and is not bound by the constraints of steady-state aerodynamics. The induced power is calculated as the mean rate of increase of wake kinetic energy. The remaining components of the flight power (parasite and profile) are calculated by the traditional methods; there is some consideration of different representations of body parasite drag. The lift coefficient required for flight is also calculated; for virtually all birds the lift coefficient in slow flight and hovering is too large to be consistent with steady-state aerodynamics. A bird is concerned largely to reduce its power consumption on all but the shortest flights. The model suggests that there are several ways in which power reduction can be achieved. These various strategies are in good agreement with observation.

Rayner, J. M. V.

"A VORTEX THEORY OF ANIMAL FLIGHT. PART 1. THE VORTEX WAKE OF A HOVERING ANIMAL"

Journal of Fluid Mechanics, Vol. 91, part 4, 1979, pp. 697-730.

The distribution of vorticity in the wake of a hovering bird or insect is considered. The wake is modelled by a chain of coaxial small-cored circular vortex rings stacked one upon another; each member of the chain is generated by a single wing-stroke. Circulation is determined by the animal's weight and the time for which a single ring must provide lift; ring size is calculated from the circulation distribution on the animal's wing. The theory is equally applicable to birds and insects, although the mechanism of ring formation differs. This approach avoids the use of lift and drag coefficients and is not bound by the constraints of steady-state aerodynamics; it gives a wake configuration in agreement with experimental observations. The classical momentum jet approach has steady momentum flux in the wake, and is difficult to relate to the wing motions of a hovering bird or insect; the vortex wake can be related to the momentum jet, but adjacent vortex elements are disjoint and momentum flux is periodic. The evolution of the wake starting from rest is considered by releasing vortex rings at appropriate time intervals and allowing them to interact in their own velocity fields. The resulting configuration depends on the feathering parameter f (which depends on the animal's morphology); f increases with body size. At the lower end of the wake rings coalesce to form a single large vortex, which breaks away from the rest of the wake at intervals. Wake contraction depends on f ; the minimum areal contraction of one-half (as in momentum-jet theory) occurs only in the limit $f \rightarrow 0$, but values calculated for smaller insects of just over one-half suggest that the momentum-jet may be a good approximation to the wake when f is small. Induced power in hovering is calculated as the limit of the mean rate of increase of wake kinetic energy as time progresses. It can be related to the classical momentum-jet induced power by a simple conversion factor. For an insect or hummingbird, the usual momentum-jet estimate may be between 10 and 15% too low, but for a bird it may be as much as 50% too low. This suggests that few, if any, birds can sustain aerobic hovering, and that as small a value of f as possible would be necessary if the bird were to hover. Tip losses (energy cost of the vortex-ring wake compared with the equivalent momentum jet) are negligible for insects, but can be in the range 15-20% for birds.

Raza, S. A., Sutherland, M., Etele, J. and Fusina, G.

"EXPERIMENTAL VALIDATION OF QUADROTOR SIMULATION TOOL FOR FLIGHT WITHIN BUILDING WAKES"

Aerospace Science and Technology, Vol. 67, 2017, pp. 169-180.

Experimental test flights are conducted to validate a novel simulation tool capable of predicting the effects of building generated turbulent winds on the flight performance of autonomous quadrotors. Wind conditions are modeled using time accurate Large Eddy Simulations where five representative points within the building wake are used to predict an average position hold deviation. Three control methods for autonomous position control tuned under no wind conditions are evaluated (Proportional Derivative (PD), Integral Backstepping, and Fuzzy Logic). Flight tests using a small (approximately 2 kg)

quadrotor UAV within a building wake show that the simulation tool can predict average position deviation to within a single body length (0.55 m) in the horizontal plane for observed freestream wind speeds between 1 and 2 m/s (with predicted gusts of up to ± 6 m/s). The simulation tool is also shown to be able to predict relative differences between control methods both overall and specifically along each co-ordinate axis. A PD controller is predicted to hold position more accurately with a building wake in the direction perpendicular to the freestream wind by approximately $\pm$ half a body length while a Fuzzy controller achieves the same result in the direction parallel to the freestream wind. These results are validated by flight test data where both the most effective control strategy, and the magnitude of the position control difference, are shown to match the simulation results.

Razdobarin, A. M.

"COMPUTATION OF THE INFLUENCE OF UNSTEADY GUSTS ON FLOW ABOUT AN AIRFOIL SECTION"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 164-168

The problem of computing gas flow with unsteady gusts about an airfoil section is considered. A description of a numerical methodology used in the computation is given. The results of the computation of the aerodynamic loading of a NACA 0012 profile in steady flow and in flow with vertical gusts are presented. [In Russian]

Rebours, R. and Rokhsaz, K.

"FLAP SIZING FOR WAKE VORTEX INSTABILITY"

SAE Paper 2000-01-1693, May 2000, Wichita, KS

The authors explore the possibility of designing the flap system on a given wing for enhanced Crow instability. The problem motivation in terms of increased traffic volume and increased safety is described. A brief review of the technical literature is given. An exploratory two-dimensional potential flow formulation is presented. A generic wing and flap combination is used for trade-off studies. The authors show that the frequency with which the flap-tip and the wing-tip vortex filaments swirl around each other can be tuned to match that which corresponds to the largest rate of amplitude growth in the wake. The extent of the analysis being two-dimensional, the authors suggest careful wind- or water-tunnel testing in three dimensions to validate the concept.

Rebours, R., Kliment, L. K. and Rokhsaz, K.

"FORCED RESPONSE OF A VORTEX FILAMENT PAIR MEASURED IN A WATER TUNNEL"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1163-1168

Crow instability is examined and quantitative measurements made in a water tunnel are presented. The results of the application of a novel technique for quantitative data acquisition that allows

measurement of the vortex strength, the oscillation frequency of the vortex filaments, and the rate of growth of their amplitude simultaneously, are presented. A pair of vortex filaments, typical of those of wing-tips, is created by individual vortex generating blades in a water tunnel. The filaments are then subjected to periodic inputs, and their responses are measured downstream. The vortex system is excited over a range of frequencies. The filaments are visualized with dye injection, whereas their cross sections are illuminated with light sheets at different downstream locations. Time history of the vortex position is extracted from video recordings of the illuminated cross sections. The results show that most of the essential features associated with Crow instability, such as the inclination angle of the plane of vortex motion and the growth rate of the amplitude, are in qualitative agreement with the theoretical model. Disagreements between theoretical and experimental results are examined and discussed. These experiments prove the viability of the experimental approach. Furthermore, the results demonstrate clearly that manipulation of the excitation frequency can control the rate of growth of amplitude.

Rebours, R., Kliment, L. K. and Rokhsaz, K.

"FORCED RESPONSE OF A VORTEX FILAMENT PAIR MEASURED IN A WATER TUNNEL"

AIAA Paper No. 2001-2448, June 2001, Anaheim, CA.

This paper examines Crow instability and presents quantitative measurements made in a water tunnel. The authors present the results of applying a novel technique for quantitative data acquisition that allows measuring the vortex strength, the oscillation frequency of the vortex filaments, and the rate of growth of their amplitude simultaneously. A pair of vortex filaments, typical of those of wing tips, is created by individual vortex generating blades in a water tunnel. The filaments are then subjected to periodic inputs and their responses are measured downstream. The vortex system is excited over a range of frequencies. The filaments are visualized using dye injection while their cross sections are illuminated with light sheets at different downstream locations. Time history of the vortex position is extracted from video recordings of the illuminated cross sections. The results show that most of the essential features associated with Crow instability, such as the inclination angle of the plane of vortex motion and the growth rate of the amplitude are in qualitative agreement with the theoretical model. Disagreements between theoretical and experimental results are examined and discussed. These experiments prove the viability of the experimental approach. Furthermore, the results demonstrate clearly that manipulating the excitation frequency can control the rate of growth of amplitude.

Reddy, K. R.

"ROTOR WAKE MODELLING METHODS SURVEYED DURING AN OVERSEAS VISIT"

AR-004-474, Aerodynamics Technical Memorandum 381, 1986, Aeronautical Research Laboratories, Melbourne, Australia.

Between 8th September and 9th October 1985, the author attended the Eleventh Rotorcraft Forum in London, and visited ten research Establishments in England, West Germany, and the USA. The main purpose of the overseas visit was to investigate rotor wake modelling methods currently used. A report is given on the Forum attendance and discussions held at the establishments, together with a general review of rotor wake modelling.

Reddy, K. R.

"PREDICTION OF HELICOPTER ROTOR DOWNWASH IN HOVER AND VERTICAL FLIGHT"

ARL/AERO-REPT-150, January 1979, Aeronautical Research Labs, Melbourne, Australia

A vortex-wake method to calculate the rotor downwash in hovering and vertical flight is presented. The blade is represented by a lifting line. The rotor wake is simulated by a vortex sheet and a series of rolled up root and tip vortices, similar in form to that of a classical fixed wing. The concept of rectangularization of the rotor wake is used in obtaining a formula for the normal component of induced velocity. Wake contraction based on experimental data is introduced into the calculations. Numerical calculations are performed for two rotor configurations. Computed induced velocities and blade loadings are compared with the available flight data.

Reddy, K. R.

"THE VORTEX FLOW FIELD GENERATED BY A HOVERING HELICOPTER"

7th Australasian Hydraulics and Fluid Mechanics Conf., Institution of Engineers, Brisbane, August 1980

Important vortex elements in the wake of a hovering helicopter are identified based on well-established fixed wing theory. The vortex positions are specified using experimental results. To make the problem mathematically simple, Willmer's rectangularization principle is introduced. Using this wake model, the calculated velocity field and blade loading are compared with available helicopter flight data. The comparison shows that the present simple method yields satisfactory results.

Reddy, K. R.

"A ROTOR WAKE MODEL FOR FORWARD FLIGHT SIMULATION STUDIES"

ARL/AERO-NOTE-402, June 1981, Aeronautical Research Labs., Melbourne, Australia

This Note presents an attempt to develop a rotor wake model for forward flight which requires only modest computing time and, therefore, is suitable for flight simulation studies. Free and rigid wake models are discussed, together with various simplifying assumptions, in order to reduce the computation time to acceptable levels for simulation studies. Using a tip vortex wake model and the Biot-Savart relation, induced velocities are calculated in the rotor plane. It is then assumed that the tip vortex wake takes the form of a skewed helix. Such a simple prescribed model requires little computing

time and the accuracy of its results when compared with more elaborate free wake models shows considerable promise.

Reddy, K. R.

"VORTICITY IN THE WAKE OF A HELICOPTER ROTOR IN FORWARD FLIGHT"

8th Australasian Fluid Dynamics Conf., University of Newcastle, Nov. 1983.

In this paper, important vortex elements in the wake of a helicopter rotor are first identified. Various simplifying assumptions are then introduced to reduce the computational time to acceptable levels. Using a blade tip vortex model, several wake geometries have been investigated. The results show that a simple skewed helical vortex wake model provides acceptable results for helicopter flight simulation and performance studies.

Reddy, K. R. and Stewart, C. J.

"SIMULATION, A VALUABLE TOOL IN THE ESTIMATION OF HELICOPTER FLIGHT DYNAMIC CHARACTERISTICS"

18th World IMACS/MODSIM Congress, July 2009, Cairns, Australia, pp. 1643-1649.

Estimating helicopter flight dynamic characteristics is a challenge. Manufacturers of the aircraft generally establish these characteristics by flight testing over a range of operational conditions. However, it is not always possible to test the aircraft in certain conditions. Simulation can play an important role in filling the gaps between the flight test data sets and extending the operating limits beyond the boundaries of the test envelope. A helicopter flight dynamic simulation requires a representation of the aerodynamics, dynamics, and control systems. In this paper we model an important component of aerodynamics, that is, the rotor wake flow field. This very complex flow condition is often unsteady and dominated by vorticity. Important elements of the rotor wake vorticity are identified, then simplified (using a vortex sheet to represent the near wake of the rotor blade, and vortex rings to represent the intermediate and far wake) and then applied to mathematically simulate helicopter vertical flight conditions. Using this simple flow model, helicopter velocity and blade loadings have been calculated for hovering flight and compared with published data, including test data, to establish the validity of the model. The model has been extended to capture unusual blade loading associated with vertical flight including vertical gust effects and vortex ring states. It is difficult to safely and repeatably replicate such flight conditions during flight tests. By hypothesizing helicopter flight as the flow represented by the generation and interaction of two jets of varying strength the unsteady flow can be better understood. The rotor can be seen to be producing one jet; the other is produced by the motion of the helicopter through the air. These two jets will interact producing a region of unstable flow. As the descent rate of the helicopter increases the location of the interface moves closer to the rotor disc and influences its lift generating capacity. Using the simple flow model, we can simulate flight conditions, often in unsteady flow states, and extract meaningful data. Numerical

simulations and results are presented in this paper for a range of operating conditions associated with helicopter vertical flight..

Reddy, S. R., Sobieczky, H., Abdoli, A. and Dulikravich, G. S.

"WINGLETS -- MULTIOBJECTIVE OPTIMIZATION OF AERODYNAMIC SHAPES"

11th World Congress on Computational Mechanics (WCCM XI), July 2014, Barcelona, Spain.

Various configurations for airplane wing tip winglets have been investigated by performing 3D aerodynamic analysis. An existing blended winglet has been equipped with a secondary lower element to create a split winglet configuration. At winglet tips, a trailing edge extension was added to create scimitar streamwise spikes. A total of eight variables were used to define the winglet geometry. The presented design methodology utilizes a second order continuous, 3D geometry generation algorithm based on locally analytical surface patches. This algorithm requires a minimal number of design parameters to be varied in order to create vastly different 3D geometries of the winglets attached to a clean wing which is blended with the fuselage. A 3D, compressible, turbulent flow analysis was performed using a Navier-Stokes solver on each configuration to obtain objective function values. Each configuration was analyzed at free stream Mach number of 0.25 and an angle of attack of 11 degrees to mimic takeoff conditions of a passenger aircraft. Multi-objective optimization was carried out using modeFRONTIER utilizing a radial basis function response surface approximation coupled with a generic algorithm. Maximizing coefficient of lift and lift-to-drag ratio, while minimizing coefficients of drag and magnitude of coefficient of moment, were the four simultaneous objectives. Performance benefits of individual components of the optimized geometry were also investigated.

Reed, III, W. H.

"AN ANALYTICAL STUDY OF THE EFFECT OF AIRPLANE WAKE ON THE LATERAL DISPERSION OF AERIAL SPRAYS"

NACA TR-1196, January 1954, NACA Langley Aero. Lab., Langley Field, VA

Calculations are made to determine the trajectories of liquid droplets introduced into the air disturbances generated by an airplane engaged in aerial spraying. The effects of such factors as the positions at which droplets are ejected into the disturbances, airplane lift coefficient, and altitude are investigated. The distribution of deposit on the ground is computed for several droplet-size spectra, variations in the rate at which mass is ejected along the span, and lateral flight-path spacings. Consideration is then given to the problem of adjusting these factors with the aim of improving the uniformity and increasing the effective width of the deposit. The results indicate that the lateral dispersion of droplets is increased when the spanwise position at which particles are ejected is moved toward the wing tip. Greater dispersion also results when the airplane lift coefficient or altitude is increased.

Reed, Jr., R. E.

"PROPERTIES OF THE LATERAL RANDOM OSCILLATIONS OF TRAILING VORTICES OBSERVED IN WIND-TUNNEL TESTS"

NEAR TR-47, January 1973, Nielsen Engineering and Research Inc., Mountain View, CA

The characteristics and causes of the lateral oscillations of trailing vortices observed during tests in the 40- by 80-foot and 7- by 10-Foot Wind Tunnels at Ames Research Center are studied. Various statistical properties of the oscillations are computed from movie camera data. A comparison of these data with a derived analytical expression indicates that the vortex oscillation is caused by the tunnel turbulence and the rms amplitude is independent of the properties of the vortex for the range of parameters considered.

Reeder, J. P., Taylor, R. T. and Walsh, T. M.

"NEW DESIGN AND OPERATING TECHNIQUES FOR IMPROVED TERMINAL AREA COMPATIBILITY"

SAE Paper No. 740454, Dallas, TX, 1974

Current aircraft operating problems that must be alleviated for future high-density terminal areas are safety, dependence on weather, congestion, energy conservation, noise, and atmospheric pollution. The microwave landing system (MLS) under development by FAA provides increased capabilities over the current ILS. It is however, necessary and urgent to develop the airborne system's capability to take maximum advantage of the MLS capabilities to solve the terminal area problems previously mentioned. A major limiting factor in longitudinal spacing for capacity increase is the trailing vortex hazard. Promising methods for causing early dissipation of the vortices are being explored. Also, flight procedures for avoiding the hazard will be explored.

Rees, F. L.

"METHOD OF DETECTING WEATHER CONDITIONS IN THE ATMOSPHERE"

US Patent 6,034,760, March 2000

Method and apparatus for detecting conditions in the atmosphere which are hazardous to flying aircraft and providing early warning to pilots or ground personnel. The method includes using a laser beam and a coherent optical receiver to optically sense sound waves produced by those hazardous conditions and measuring the effect of those sound waves on the transmitted and received optical beams.

Refan, M., Hangan, H. and Siddiqui, K.

"PARTICLE IMAGE VELOCIMETRY MEASUREMENT OF TORNADO-LIKE VORTICES COMPARED WITH DOPPLER RADAR DATA"

17th International Symposium on Application of Laser Techniques to Fluid Mechanics, July 2014, Lisbon, Portugal.

Particle Image Velocimetry (PIV) technique was employed to characterize the flow field of simulated tornado vortices and to establish a relationship between laboratory generated tornadoes and the field ones. Field data collected by mobile Doppler radars were analyzed using a mathematical method namely the Ground-based Velocity Track Display and the velocity fields were extracted. The horizontal velocity field of tornado vortices, simulated in Model WindEEE Dome, was measured using PIV for a wide range of vortex intensity. The substantial mismatch between the averaging time of the full-scale data and the laboratory data which is originated in the very small length scale of the simulation and the low sampling rate of the PIV system, was addressed and corrected using the Durst curve. Once modified, the velocity field of the simulated vortex was compared with that of the full-scale tornado and the swirl ratio of the field tornado as well as the length and velocity scales of the simulation were identified. This practice, for the first time, provided an opportunity to compare the velocity field of tornado vortices obtained through PIV and radar measurements using proper scaling.

Rehback, C.

"NUMERICAL STUDY OF THE INFLUENCE OF THE WING TIP SHAPE ON THE VORTEX ROLL UP"

NASA-TT-F-14538, August 1972, Scientific Translation Service, Santa Barbara, CA

A computer program to analyze the wing tip vortex distribution as a function of wing tip shape is presented. The wing and the sheet are replaced by a vortex surface. The continuous vortex distribution over the surface is replaced by a discrete vortex distribution, which is a horseshoe distribution of finite magnitude and is placed over the wing only. The shear appears in the form of a series of vortex threads which emanate at moderate incidence angles from the leading edge to the wing tip. Starting with the given initial position, the threads evolve during the course of an iteration calculation and assume equilibrium positions parallel to the average velocity over the sheet.

Rehm, F.

"PREDICTION OF AIRCRAFT DELAYS AS A FUNCTION OF WEATHER"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

The impact of the weather on the delay of flights is often underestimated when simulating airport scenarios. However, recent studies have shown that certain weather factors influence the air traffic significantly. In this work we will show in detail, which weather factors in the closer region of a big international airport have an impact on the delay of flights in which extent. Beside the results of a linear regression model, we will also present in this paper the results of some modern data mining approaches, such as neuronal networks and fuzzy clustering techniques. We will show that several weather situations have a similar influence on the delay of flights. Our analyses focus the delay that will be explicitly caused by weather factors in the vicinity of the airport, the so-called traffic

management area (TMA). Thus, delay caused by some weather influences on the departure airport or by other circumstances during the flight, will not bias our results. With our methods it becomes possible to predict the delay of flights if certain weather factors are known. We will specify these factors and quantify their impact on delays.

Reich, P. G.

"INFLUENCE ON LAND AND AIRSPACE DEMANDS OF TECHNIQUES IN CURRENT USE"

Air Traffic, Navigation and the Community, Royal Aeronautical Society and Institute of Navigation, Symposium on Air Traffic in the 1980's, May 1970

Study of the limitations of techniques already commonly applied, and of the more promising points of application for new technology in navigation, surveillance, and traffic control. In seeking the latter, some of the current trends in other fields, particularly aircraft design, are considered. Considerable emphasis is placed on the efficient use of land at airports, in view of the strength of feelings aroused in communities by questions of apportionment and exploitation of land resources. The incidence of much stronger wing tip vortices associated with heavy CTOL aircraft is likely to make increases in land productivity difficult, if not impossible, to achieve.

Reichmuth, J.

"OPERATIONAL AND CAPACITY INVESTIGATIONS FOR THE ALLEVIATION OF WAKE VORTEX SEPARATION PROBLEMS AT THE AIRPORT OF FRANKFORT"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 26-1 - 26-23

Since 1989 a working group named 'Capacity for Frankfurt Airport' exists with the goal to identify means by which an increase of capacity at Frankfurt airport would be possible. One candidate was a wake vortex warning system for the two parallel runways at Frankfurt, separated only 517 m. Up to now work related to a wake vortex warning system was done in three main areas. Field measurements were performed at Frankfurt airport to obtain the necessary knowledge about vortex propagation and structure in the boundary layer. The feasibility of a prognostic system which predicts the behavior of the wake vortices under different meteorological conditions was investigated. The outcome of these measurement is that a prediction about wake vortex free regions can be made up to 20 min. and that a situation where the two parallel runways at Frankfurt could be operated independent of wake vortices would be present 60% of the time. Fast Time Simulations with the programs SIMOD and ADSIM were used to model the airspace structure of Frankfurt and the behavior of aerodrome traffic from arrival to departure. These programs are now able not only to simulate the present situation but also the effects on capacity and delays due to changes induced by a wake vortex warning system operationally. These fast time simulations predict an increase of arrivals of 1 to 5 aircraft per hour. Real Time Simulation allowed a closer look on three different operational concepts under well-defined conditions. Controllers and pilots were involved in the concept development phase early. This helps to find

displays and operations acceptable for a realistic environment. The present paper concentrates on the real time simulations performed in June and July this year. The implementation in the simulator environment will be described together with the three different operational concepts under simulation.

Reimer, H. M. and Vicroy, D. D.

"A PRELIMINARY STUDY OF A WAKE VORTEX ENCOUNTER HAZARD BOUNDARY FOR A B737-100 AIRPLANE"

NASA TM-110223, April 1996, Langley Research Center, Hampton, VA

A preliminary batch simulation study was conducted to define the wake decay required for a Boeing 737-100 airplane to safely encounter a Boeing 727 wake and land. The baseline six-degree-of-freedom B737 simulation was modified to include a wake model and the strip-theory calculation of the vortex-induced forces and moments. The guidance and control inputs for the airplane were provided by an autoland system. The wake was positioned such that the desired flight path traversed the core of the port vortex. Various safe landing criteria were evaluated for defining a safe encounter boundary. A sensitivity study was also conducted to assess the effects of encounter model inaccuracies.

Reinholtz, C. K., Heltsley, F. L., Sirbaugh, J. R., Wehrmeyer, J. A. and Rotach, D. G.

"STEREO-PIV DATA OBTAINED BEHIND AN F-15 MODEL COMPARED TO CFD RESULTS"

AIAA Paper 2008-3712, June 2008, Seattle, WA

A stereoscopic Particle Image Velocimetry (PIV) system has recently been implemented in the Aerodynamic Wind Tunnel 4T at Arnold Engineering Development Center. Sequences of instantaneous three-component velocities were obtained in the wake of a 1/20th scale F-15 model in a 40- by 40-cm planar region situated perpendicular to the tunnel's freestream flow. Data sets were obtained in Mach number 0.4 flow at eight different model attitudes. A preliminary comparison between PIV results and computational fluid dynamics (CFD) solutions shows similar counter-rotating wake structures. This paper compares experimental PIV data with CFD predictions.

Reinschke, J., Mohring, W. and Obermeier, F.

"SCATTERING OF SOUND WAVES BY A CYLINDRICAL VORTEX: A SEMI-ANALYTICAL THEORY"

J. Fluid Mech., Vol. 333, 1997, pp. 273-299

A semi-analytical theory for the scattering of plane sound waves by a compressible, non-homentropic, circular-cylindrical, single vortex is presented in this paper. As a special case, the scattering of sound by a cylindrical inhomogeneity (hot spot) is investigated. Contrary to the otherwise analogous quantum-mechanical scattering problem, there are singularities in the modified acoustic wave equation when the scattering by a vortex is considered. It will be shown how these singularities can be treated. This sound-scattering theory is applied to the problem of the interaction of weak plane shock waves with a

strong cylindrical vortex. The calculated scattered sound signal has a rather complicated structure in which a cylindrical wave with an essentially quadrupolar directivity pattern is discernible. In the case of shock-hot-spot interaction a scattered sound signal with dipole-like amplitude is obtained. Both results qualitatively agree with experimental findings.

Reitebuch, O.

"WIND LIDAR FOR ATMOSPHERIC RESEARCH"

In: Atmospheric Physics, Research Topics in Aerospace, U. Schumann (editor), Springer-Verlag Berlin Heidelberg, 2012 pp. 487-507.

Wind lidars use the optical Doppler effect to measure the atmospheric wind with high spatial and temporal resolution. This offers a wide range of applications from aircraft wake vortex detection and characterization to measurement of turbulent quantities like fluxes to resolving small and mesoscale atmospheric flows, and even global wind profiling from space in the future. Principles of wind lidars including two complementary techniques and applications for atmospheric research are discussed.

Remaly, M. A.

"DEVELOPMENT OF A LABORATORY SCALE AIRCRAFT WAKE VORTEX DETECTION SYSTEM"

College of Engineering Research Symposium, Penn. State University, University Park, PA, March 2006

Aircraft wake vortices have a major impact on the efficiency of airports due to minimum separation requirements. Encountering a leading aircraft's wake could be hazardous to a following aircraft. A system known as a Radar Acoustic Sounding System (RASS) has been used to measure the strength of these vortices for aircraft on approach for landing. However, that system was adapted from a RASS that was initially designed for meteorological purposes. It is therefore the purpose of this research to contribute to the development of a RASS designed specifically for wake vortex detection and measurement by designing and testing a sub-scale laboratory system. The primary components of the sub-scale system are the radar transmitter/receiver and an acoustic array. In addition, a swirling jet facility will be used to generate a flow field that will simulate a single aircraft trailing vortex.

Remaly, M. A.

"DEVELOPMENT OF A LABORATORY SCALE AIRCRAFT WAKE VORTEX DETECTION SYSTEM"

M.S. Thesis, December 2006, Pennsylvania State University, University Park, PA

NASA is developing an Advanced Vortex Sensing System (AVOSS) which, if implemented, would be used to monitor and predict wake vortices to support Reduced Spacing Operation (RSO) and increase Terminal Area Productivity (TAP). A Radar Acoustic Sounding System (RASS) has been used by researchers as the vortex sensing component of the AVOSS and results have shown good agreement with known vortex properties; however, that system was originally designed for meteorological

purposes. It was therefore the overall goal of this thesis to develop a laboratory scale vortex system based on a RASS. The sub scale system permits a cost-effective method for carefully evaluating each component of the sensing system to ensure optimum vortex sensing characteristics. Contained in this thesis are the experimental studies and development of a 24 kHz acoustic array used to generate a highly directed beam, and a 10.4 GHz radar system for tracking the acoustic waves. Additionally, a swirling jet facility was developed and characterized to simulate a single aircraft wake vortex; experimental techniques included flow visualization, Particle Image Velocimetry, and a five-hole pitot probe. Laboratory RASS experiments, however, were unable to detect an acoustically induced echo above the background reflections from the sidewalls of the laboratory. Consequently, the swirl jet's flow field was never interrogated by the RASS. However, several important results, conclusions, and system design considerations are presented and provide the ground for future work to successfully develop a laboratory scale system.

Ren, L. and Clarke, J.-P. B.

"FLIGHT-TEST EVALUATION OF THE TOOL FOR ANALYSIS OF SEPARATION AND THROUGHPUT"

Journal of Aircraft, Vol. 45, No. 1, January-February 2008, pp. 323-332

The tool for analysis of separation and throughput has been developed to predict the range of possible trajectories of aircraft performing any given continuous descent arrival and thereby determine the minimum target spacing at a metering point, such that there is a high probability of no separation violations thereafter. The resulting reduced need for controller intervention is expected to facilitate the implementation of continuous descent arrival. This tool includes a fast-time Monte Carlo trajectory simulator and a theoretically rigorous separation analysis methodology based on the probabilistic characteristics of trajectories. The tool was used to determine the target spacing for a continuous descent arrival flight test conducted in September 2004 at Louisville International Airport. Results of the flight test indicate that the 15-n-mile target spacing yielded a conditional probability of 69.6% for the continuous descent arrival to runway 35L, very close to the predicted value of 68.6%; and an overall total probability of 81.7%, which is between the predicted values of 79.6% and 85.0% for the continuous descent arrival to runway 35L and 17R, respectively. The flight test demonstrated that, by using the tool as developed, continuous descent arrival can be efficiently implemented under moderate to moderately high traffic conditions, thereby achieving much needed environmental and economic benefits.

Ren, M., Elsenaar, A., van Heijst, G. J. F., Kuczai, A. K. and Geurts, B. J.

"DECAY OR COLLAPSE: AIRCRAFT WAKE VORTICES IN GRID TURBULENCE"

Euromech Fluid Mechanics Conf. (EFMC6), June 2006, Stockholm, Sweden.

Trailing vortices are naturally shed by airplanes and they typically evolve into a counter-rotating vortex pair. Downstream of the aircraft, these vortices can persist for a very long time and extend for several kilometers. This poses a potential hazard to following aircraft, particularly during take-off and

landing. Therefore, it is of interest to understand what effects control the decay rate in strength of the trailing vortices. The decay of aircraft wake vortices is strongly dependent on weather conditions. To simulate an environment of atmospheric turbulence, homogeneous isotropic turbulence is introduced next to localized vortical structure. In this contribution, the effect of external turbulence on the vortex decay will be investigated numerically, using a DNS method, and experimentally. Wind tunnel experiments are carried out using a smoke visualization technique.

Ren, T. and Edwards, J. A.

"VORTEX INTERACTION WITH AN AEROFOIL USING CHIMERA AND THE AMR ALGORITHM"

AIAA Paper No. 2002-4806, Monterey, CA, August 2002

Recently, a solution adaptive Chimera grid scheme applying the structured Adaptive Mesh Refinement (AMR) algorithm has been developed by the authors for simulating multiple and moving body supersonic flows. Two CFD methodologies, the Chimera grid method and the AMR algorithm were integrated. A complex multiple and moving body configuration can be easily meshed by the Chimera grid method, and each domain of the initial coarse Chimera grid system is then adapted by the AMR algorithm according to the flow solution. The advantages of the Chimera grid method and the AMR algorithm are combined. In this paper, numerical solutions of a shock interaction with an airfoil, together with the subsequent interaction of a vortex generated at the trailing edge of the airfoil interacting with a further airfoil are presented. The results are obtained from this new solution adaptive Chimera grid scheme (AMRC code) and are analyzed and compared with both experiment and previous computational results. The simulations demonstrate the flexibility of grid generation and the high efficiency and the ability to resolve and track complex flow features.

Renac, F., Sipp, D. and Jacquin, L.

"CRITICALITY OF COMPRESSIBLE ROTATING FLOWS"

Physics of Fluids, Vol. 19, 2007, pp. 018101 -- 1-018101-4

The effect of compressibility on the criticality of swirling subsonic flows is investigated. This study extends previous works by Rusak and Leo [J. Fluid Mech., 461, 301 (2002); 501, 25 (2004)] on the critical swirl of subsonic vortex flows in a circular straight pipe. We derive an asymptotic solution in the case of an isothermal plug-flow with solid-body rotation. Physically, compressibility is found to slow down phase and group velocities of axisymmetric Kelvin waves, thus decreasing the rotation contribution to flow criticality. It is shown that compressibility damps the stretching mechanism which contributes to the wave propagation in the incompressible limit.

Renaud, T., Le Pape, A. and Benoit, C.

"UNSTEADY EULER AND NAVIER-STOKES COMPUTATIONS OF A COMPLETE HELICOPTER"

31st European Rotorcraft Forum, September 2005, Florence, Italy.

The simulation of the aerodynamic interactions between the different parts of a helicopter becomes more and more important for the understanding of the complex flowfield and the design of the helicopter. Advanced numerical tools have been developed in the elsA solver to represent the various phenomena which occur around the helicopter. Recent progresses have been achieved within the French-German cooperation CHANCE (Complete Helicopter AdvANced Computational Environment) which aims at the numerical simulation of a complete helicopter. This paper presents results of unsteady Euler and Navier-Stokes computations, using Chimera techniques. The first test-case concerns a Dauphin 365N configuration with its main rotor. A numerical analysis (time convergence, mesh refinement, ...) allowed to find the best choices for such a complex unsteady simulation. The CFD solutions are in good agreement with measurements done on a Dauphin helicopter model. In the second part, an automatic Cartesian grid approach is applied on a complete configuration (wind tunnel model like the NH90 helicopter) in pitch-up flow conditions. The Euler simulation allows to describe the complex flowfield and the interactions between the fuselage and the two rotors.

Rennich, S. C.

"ACCELERATED DESTRUCTION OF AIRCRAFT WAKE VORTICES"

Ph.D. Thesis, May 1997, Stanford Univ., Palo Alto, CA

An aircraft's wake often breaks down via the Crow instability. No instability has yet been found which is more rapidly growing or shows a greater ability to mix vorticity of opposite sign than the Crow instability. Thus, the objective of this research is to investigate alleviation schemes by which perturbations, applied to the wake at the wing, survive the roll-up process, excite the Crow instability at large amplitude and lead to accelerated destruction of the wake vortices. To carry out this research, a new, numerical method has been developed which solves the incompressible Navier-Stokes equations in vorticity form in a domain which is periodic in one direction and unbounded in the other two. A code using this method has been used to fully characterize the Crow instability as it exists in a 3D, viscous environment and validate the analytical models of this instability. Finally, a new mechanism to be used in accelerating the destruction of aircraft wake vortices is proposed. Its behavior is investigated using both Navier-Stokes and vortex filament methods. The results indicate that the time required for vortex linking can be reduced by as much as a factor of seven when compared to the time required for equivalent growth via the linear Crow instability.

Rennich, S. C. and Lele, S. K.

"NUMERICAL METHOD FOR INCOMPRESSIBLE VORTICAL FLOWS WITH TWO UNBOUNDED DIRECTIONS"

Journal of Computational Physics, Vol. 137, 1997, pp. 101-129

A new, efficient, and accurate method has been developed for computing unsteady, incompressible, viscous flows in a domain where two dimensions are unbounded, the third dimension is periodic and the vorticity is rapidly decaying in the unbounded directions. We use the term unbounded to mean

doubly infinite (no boundaries of any kind). This is an extension of the methods described by others for flows with two periodic and one unbounded direction, where the irrotational velocities outside the vortical domain are treated analytically. The new method is shown to be both accurate and efficient. The method presented here has finite, but arbitrarily high order, formal accuracy, and incurs substantial additional cost for a given mesh. However, this increased cost is more than offset by the reduction in the number of mesh points required for a given accuracy. The result is that for accurate computations, the present method can be orders of magnitude more efficient than others currently in use. This paper presents the method, discusses implementation issues, validates its accuracy, and presents sample calculations.

Rennich, S. C. and Lele, S. K.

"DIRECT NUMERICAL SIMULATION OF THE BREAKDOWN OF AIRCRAFT WAKE VORTICES"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 30-1 to 30-10

An investigation is initiated that aims to improve the understanding of how disturbances to aircraft vortex wakes, applied at the wing, survive the roll-up process and eventually lead to destruction of the wake. To efficiently perform this investigation, a numerical method is presented which accurately and efficiently computes flows in domains that are unbounded in two directions and periodic in the third, subject to the condition that vorticity is compactly distributed in the unbounded directions. This new code is used to compute the growth of symmetric disturbances on a pair of counter rotating columnar vortices and, for high Reynolds number, the inviscid, linear vortex filament results of Crow which predict the most unstable wavelength and its amplification rate, are reproduced well. From these computations an eigenfunction of the Crow instability as it exists in an evolving viscous vortex pair is extracted. The evolution of a perturbed plane wake due to an elliptically loaded wing is computed. It is observed that a perturbation of the correct wavelength rapidly evolves into the Crow instability and grows at approximately the predicted rate.

Rennich, S. C. and Lele, S. K.

"METHOD FOR ACCELERATING THE DESTRUCTION OF AIRCRAFT WAKE VORTICES"

J. Aircraft, Vol. 36, No. 2, March-April 1999, pp. 398-404

The wake vortices shed by large aircraft and their associated hazard to following aircraft remain an important issue in commercial aviation. Extensive research into methods for alleviating this wake vortex hazard has been continuing for many years. This paper presents results from numerical simulations detailing a potentially useful mechanism for accelerating the destruction of the aircraft vortex wake and reducing the wake hazard. The term 'destruction' is used to refer to the progressive annihilation of the wake caused by mixing of vorticity of opposite sign and the associated elimination of large coherent structures. The emphasis here is on a description of the mechanism and its connection to previous work.

Rennick, S. C.

"A TRANSPORT CANADA PERSPECTIVE"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 21-23

This presentation will briefly describe Transport Canada's interest and participation in wake vortex research, and, in general terms, outline suggested requirements in the development of a wake vortex forecasting system.

Renzoni, P., D'Alascio, A., Kroll, N., Peshkin, D., Hounjet, M. H. L., Boniface, J.-C., Vigevano, L., Milano, L., Allen, C. B., Dubuc, L., Righi, M., Schoell, E. and Kokkalis, A.

"EROS: A EUROPEAN EULER CODE FOR HELICOPTER ROTOR FLOW SIMULATIONS"

ICAS 1998, Paper 98-2.6.1, Sept. 1998, Melbourne, Australia.

The helicopter rotor flow field is one of the most complex and challenging problems in applied aerodynamics. Its accurate analysis is essential in the design of rotors with increased performance and in the development of rotors with reduced vibratory loads and with more environmentally-friendly acoustic signatures. There is an industrial need in Europe for a rotor aerodynamic tool able to capture rotational phenomena, such as blade tip and wake vortices, and to predict correctly the unsteady blade pressures over a range of different flight conditions. The EROS project addresses this need by developing a common European system capable of analyzing the inviscid rotor flow environment by solving the 3D Euler equations. The method is based on a proven-technology time-accurate Euler formulation on overlapping structured grids (Chimera method). The grid generator provides an all-in-one capability for grid generation guiding the user from the generation of individual component grids to the Chimera domain decomposition through an interactive process which has embedded visualization and animation capabilities. The cell-centered finite-volume solver adopts a dual-time implicit scheme on deforming grids. Nonconservative interpolation is used to transfer information across grid overlap regions. The current capabilities of the code are presented and future developments are described.

Report, DTFWA-16-D-00005, May 2019.

"This report entitled, 'Final Report on Avionics Prototype and Demonstration Test Flights' describes the Paired Approach Flight Demonstration and discusses significant findings, lessons learned, and future work recommendations. This work was funded by the FAA NextGen organization."

Rethore, P.-E.

"WIND TURBINE WAKE IN ATMOSPHERIC TURBULENCE"

1785

PhD Thesis, October 2009, Aalborg University, Aalborg, Denmark. Also is report Riso-PhD-53(EN), October 2009, Riso National Laboratory for Sustainable Energy, Roskilde, Denmark.

This thesis describes the different steps needed to design a steady-state computational fluid dynamics (CFD) wind farm wake model. The goal of the project was to design a tool that could analyze and extrapolate systematically wind farm measurements to generate wind maps to calibrate faster and simpler engineering wind farm wake models. The most attractive solution was the actuator disc method with the steady state k-e turbulence model. The first step to design such a tool is the treatment of the forces. This thesis presents a computationally inexpensive method to apply discrete body forces into the finite-volume flow solver with collocated variable treatment (EllipSys), which avoids the pressure-velocity decoupling issue. The second step is to distribute the body forces in the computational domain accordingly to rotor loading. This thesis presents a generic flexible method that associates any kind of shapes with the computational domain discretization. The special case of the actuator disc performs remarkably well in comparison with Conway's heavily loaded actuator disc analytical solution and a CFD full rotor computation, even with a coarse discretization. The third step is to model the atmospheric turbulence. The standard k-e model is found to be unable to model at the same time the atmospheric turbulence and the actuator disc wake and performs badly in comparison with single wind turbine wake measurements. A comparison with a Large Eddy Simulation (LES) shows that the problem mainly comes from the assumptions of the eddy-viscosity concept, which are deeply invalidated in the wind turbine wake region. Different models that intent to correct the k-e model's issues are investigated, of which none of them is found to be adequate. The mixing of the wake in the atmosphere is a deeply non-local phenomenon that is not handled correctly by an eddy-viscosity model such as k-e.

Rethore, P.-E., Sorensen, N. N. and Bechmann, A.

"MODELLING ISSUES WITH WIND TURBINE WAKE AND ATMOSPHERIC TURBULENCE"

Third Conference, Torque 2010, The Science of Making Torque from the Wind, June 2010, Heraklion, Crete, Greece.

The steady-state CFD turbulence models available to simulate the atmospheric boundary layer and wind turbine wake are not performing satisfyingly compared with measurements. This paper demonstrates that, in those specific cases, they operate outside of their constitutive assumptions. Several correction-models proposed in the literature are analyzed and compared with Large Eddy Simulation. None of them are found to restore the physics of the problem.

Rethore, P.-E., Sorensen, N. N., Bechmann, A. and Zhale, F.

"STUDY OF THE ATMOSPHERIC WAKE TURBULENCE OF A CFD ACTUATOR DISC MODEL"

2009 European Wind Energy Conference and Exhibition, March 2009, Marseille, France.

Modelling wind turbine wake using the standard kappa-epsilon atmospheric turbulence model gives a too fast wake dissipation compared to measurements and more advanced turbulence models. The

problem is that the relevant scales of turbulence are different from the point of view of the wind turbines and from the point of view of the terrain. As the atmospheric turbulence model imposes the scale of turbulence, part of the influence of the wind turbine on the airflow is happening at the turbulence level. It becomes therefore necessary to add terms in the turbulence equations to account for the wind turbine activity. In this context two different models are compared together and with wind turbine wake measurements. With the proper parameterization, they are both able to produce similar results, in agreement with the measurements.

Reuder, J., Baserud, L., Kral, S., Kumer, V., Wagenaar, J. W. and Knauer, A.

"PROOF OF CONCEPT FOR WIND TURBINE WAKE INVESTIGATIONS WITH THE RPAS SUMO"

Energy Procedia, Vol. 94, 2016, pp. 452-461.

The Small Unmanned Meteorological Observer (SUMO) has been operated in the vicinity of five research turbines of the Energy Research Centre of the Netherlands (ECN) at the test site Wieringermeer. The intention of the campaign was to proof the capability of the system for wind turbine wake investigations also for situations above rated wind speed. In rather high wind conditions of 15-20 m/s on May 10, 2014, the system showed a satisfying in-flight behavior and performed five racetrack flights. The racetrack patterns flown parallel to the row of the five turbines (four flights downstream the turbine row, one upstream) enable the characterization and investigation of the strength, i.e. the reduction in the mean wind, and structure, i.e. the horizontal extension and turbulent kinetic energy (TKE) distribution of single turbine wakes.

Revell, A., Iaccarino, G. and Wu, X.

"ADVANCED RANS MODELING OF WINGTIP VORTEX FLOWS"

Proceedings of the Summer Program 2006, Center for Turbulence Research, pp. 73-85

The numerical calculation of the trailing vortex shed from the wingtip of an aircraft has attracted significant attention in recent years. An accurate prediction of the flow over the wing is required to provide the correct initial conditions for the trailing vortex, while careful modeling is also necessary to account for the turbulence in the vortex core. As such, recent works have concluded that to achieve results of satisfactory accuracy, the use of complex turbulence modeling closures and numerical grids of considerable size is an absolute necessity. The computations here are reported for the flow over a NACA0012 half-wing with rounded wingtip at an incidence angle of 10 degrees, as measured by Chow et al. (1997). The primary aim is to assess the performance of a new turbulence modeling scheme which accounts for the stress-strain misalignment effects in a turbulent flow. This three-equation model bridges the gap between popular two equations eddy-viscosity models (EVM) and the seven equations of a RSM. Relative to a RSM, this new approach inherits the stability advantages of an eddy-viscosity scheme, together with a lower computational expense, and it has already been validated for a range of unsteady mean flows (Revell).

Revuelta, A.

"ON THE AXISYMMETRIC VORTEX BREAKDOWN OF A SWIRLING JET ENTERING A SUDDEN EXPANSION PIPE"

Physics of Fluids, Vol. 16, No. 9, September 2004, pp. 3495-3498

This Brief Communication investigates the onset and bifurcation structure of vortex breakdown in a laminar sudden expansion flow. Bifurcation diagrams for variable inlet swirl levels are determined by integration of the time dependent, incompressible, axisymmetric, Navier-Stokes equations in a sudden expansion with expansion ratio wavelength equals 2.0 and for moderately large values of the Reynolds number. As in the case of swirling flows in pipes, vortex breakdown is seen to occur associated with the emergence of a stagnation point when the Reynolds number is sufficiently small (Re less than or equal to 125 for wavelength = 2), while for larger values it appears as a fold in the solution space. The standing wave analysis for the stream tube emerging from the inlet orifice rim indicates that the local criticality of the flow is a necessary condition for the appearance of the vortex breakdown. The axisymmetric computations also reveal the unsteadiness of the non-slender solutions above Re greater than or equal to 400.

Reyna, L. G. and Menne, S.

"NUMERICAL PREDICTION OF FLOW IN SLENDER VORTICES"

Computers and Fluids, Vol. 16, No. 1, 1988, pp. 239-256.

We study the slender vortex approximation with emphasis on the high Reynolds number behavior. It is shown that the breakdown of the approximation coincides with the criticality condition as introduced by Benjamin. We study free vortices with and without an adverse pressure gradient for viscous and inviscid flows. Finally, we compare with the experimental results from Faler and Leibovich.

Reynolds, J., Pahle, J. and Hanson, C.

"DESIGN, DEVELOPMENT, AND FLIGHT EVALUATION OF PILOT DISPLAYS AND LONG-TRACK CONTROL FOR WAKE SURFING APPLICATIONS"

AIAA Paper 2018-3562, June 2018, Atlanta, GA.

From April to May 2017, the National Aeronautics and Space Administration Armstrong Flight Research Center completed a series of flights with a trail C-20A airplane surfing in the wake of a Gulfstream III airplane using a commercially available datalink as the primary communication between the two aircraft. The purpose of this test was to characterize the aerodynamic benefits received by the trail airplane flying in the upwash portion of the wake generated from the lead airplane. Lateral and vertical relative position in the wake were automatically controlled through an experimental programmable autopilot on the C-20A airplane. Long-track, the separation distance between the two aircraft, was maintained by test pilots managing throttle position using customized cockpit displays. These displays provided the pilots with throttle cues for maintaining long-track position and situational

awareness of the wake vortex relative to the position of the trail airplane. Flight testing demonstrated the ability of the pilots to use these displays to maintain a safe long-track distance, but found there to be trades between tracking performance and the frequency of throttle motion. The wake awareness display provided the pilots with adequate situational awareness of the wake vortex during the flight experiment. This paper presents a summary of the design, development, and flight evaluation of the pilot displays and long-track control.

Ribeiro, R. S.

"ANALYSIS OF WING WAKE ROLL-UP USING A VORTEX-IN-CELL METHOD"

Ph.D. Thesis, 1992, Stanford University, Palo Alto, CA

A wing producing lift generates a thin vorticity sheet behind it, called a vortex wake. This wake is convected downstream, adjusting its shape to remain force-free, and can interact with other surfaces and wakes as it does so. The determination of wake geometries and effects are of great interest in several aircraft design problems, including analysis of canard-wing interference, rotors and propeller-wing interference. This work applies a vortex-in-cell method to a singularity model for wings and wakes in steady, incompressible flow. Wings are represented by a vortex-lattice model, while wakes are formed by line vortices. The vorticity contained in the singularities is spread onto a rectangular grid, using quadratic splines based on the grid-cell dimensions. Velocities are computed from the vorticity field by an infinite boundary Fast Poisson Solver, which employs fast Sine and Cosine transforms and a boundary convolution scheme. Although the grid boundaries are placed close to the singularities, the solution is consistent with the condition of vanishing perturbations at infinity. Provisions are made to consider portions of the wakes downstream of the grid box. Velocities at points inside the grid are obtained by interpolation. The result is the removal of infinite velocities, as if a finite vortex-core model were introduced. The velocities computed with the vortex-in-cell method are used to relax the wake and to correct the singularity strengths on the wing, in a mixed iterative procedure. Several problems are studied to evaluate the performance of the method: velocity induced by single infinite and semi-infinite vortices, lift of rectangular and swept-back wings, roll-up of single wing wakes and interaction between wings and wakes in various arrangements. Solutions for these problems were compared with results from experiments and other methods. Detailed descriptions for wake geometry and accurate load distributions were obtained, even for cases where wakes intercepted wings directly. The method provides velocity values throughout the grid as part of the solution. The computational time required is controlled by the number of grid cells, not the number of singularities.

Ribeiro, R. S. and Kroo, I.

"VORTEX-IN-CELL ANALYSIS OF WING WAKE ROLL-UP"

J. Aircraft, Vol. 32, No. 5, September-October 1995, pp. 962-96.

A vortex-in-cell (VIC) method was coupled with a wing vortex-lattice model to compute steady-state wake roll up. The vorticity concentrated on the wing and wake vortex segments is distributed to a

Cartesian grid through the application of a spreading function. A sub vortex technique is introduced to refine the wake description without altering the number of wing panels. The velocity field induced by the spread vorticity is computed using an infinite domain fast Poisson solver. Interpolation provides velocities at any point inside the grid. The VIC method is used to compute velocities for a wake relaxation procedure and to correct wing panel circulations. The iterative method developed can be applied to configurations with several wings. The method was tested for various one and two-wing problems and compared with results from experiments and from other theories with very good agreement. Detailed descriptions for wake geometry and accurate load distributions were obtained, even for cases where wakes intercepted wings directly.

Ribera, M.

"HELICOPTER FLIGHT DYNAMICS SIMULATION WITH A TIME-ACCURATE FREE-VORTEX WAKE MODEL"

PhD Thesis, 2007, University of Maryland, College Park, MD.

This dissertation describes the implementation and validation of a coupled rotor-fuselage simulation model with a time-accurate free-vortex wake model capable of capturing the response to maneuvers of arbitrary amplitude. The resulting model has been used to analyze different flight conditions, including both steady and transient maneuvers. The flight dynamics model is based on a system of coupled nonlinear rotor-fuselage differential equations in first-order, state-space form. The rotor model includes flexible blades, with coupled flap-lag-torsion dynamics and swept tips; the rigid body dynamics are modeled with the non-linear Euler equations. The free wake models the rotor flow field by tracking the vortices released at the blade tips. Their behavior is described by the equations of vorticity transport, which is approximated using finite differences, and solved using a time-accurate numerical scheme. The flight dynamics model can be solved as a system of non-linear algebraic trim equations to determine the steady state solution, or integrated in time in response to pilot-applied controls. This study also implements new approaches to reduce the prohibitive computational costs associated with such complex models without losing accuracy. The mathematical model was validated for trim conditions in level flight, turns, climbs and descents. The results obtained correlate well with flight test data, both in level flight as well as turning and climbing and descending flight. The swept tip model was also found to improve the trim predictions, particularly at high speed. The behavior of the rigid body and the rotor blade dynamics were also studied and related to the aerodynamic load distributions obtained with the free wake induced velocities.

Ribner, H. S.

"THE SOUND GENERATED BY INTERACTION OF A SINGLE VORTEX WITH A SHOCK WAVE"

Report No. 61, June 1959, University of Toronto Institute of Aerophysics, Toronto, Canada.

The passage of a columnar vortex 'broadside' through a shock is investigated. The vortex is decomposed (by Fourier transform) into plane sinusoidal shear waves disposed with radial symmetry. The plane sound waves produced by each shear wave-shock interaction, known from previous work,

are recombined in the Fourier integral. The waves possess an envelope that is essentially a growing cylindrical sound wave, partly cut off by the shock. The sound wave is centered at the transmitted (and modified) vortex and the peak pressure attenuates inversely as the square root of the growing radius. The strength varies smoothly around the arc, from compression at one shock intersection to rarefaction at the other shock intersection. Comparison is made with results of a shock-tube investigation and heuristic theory by Hollingsworth and Richards in England.

Ricca, R. L.

"THE EFFECT OF TORSION ON THE MOTION OF A HELICAL VORTEX FILAMENT"

Journal of Fluid Mechanics, Vol. 273, 1994, pp. 241-259.

In this paper we analyze in detail, and for the first time, the role of torsion in the dynamics of twisted vortex filaments. We demonstrate that torsion may influence considerably the motion of helical vortex filaments in an incompressible perfect fluid. The binormal component of the induced velocity, asymptotically responsible for the displacement of the vortex filament in the fluid, is closely analyzed. The study is performed by applying the prescription of Moore and Saffman (1972) to helices of any pitch and a new asymptotic integral formula is derived. We give a rigorous proof that the Kelvin regime and its limit behavior are obtained as a limit form of that integral asymptotic formula. The results are compared with new calculations based on the re-elaboration of Hardin's (1982) approach and with results obtained by Levy and Forsdyke (1928) and Widnall (1972) for helices of small pitch, here also re-elaborated for the purpose.

Ricciardi, T. R., Wolf, W. R. and Bimbato, A. M.

"AN ASSESSMENT OF THE FAST MULTIPOLE METHOD APPLIED TO A VORTEX SHEET ROLL-UP PROBLEM"

AIAA Paper 2016-4173, June 2016, Washington, DC.

Aerodynamic wakes of large aircraft and their induced velocity may cause serious hazards to smaller aircraft, affecting the take-off and landing operations in airports. A simplified but representative model of the problem is the evolution of a vortex sheet in the Trefftz plane. In this work, we employ the discrete vortex method (DVM) accelerated by the fast multipole method (FMM) to simulate this problem. Due to the cost associated with vortex clustering, the reduction in time from $O(N^2)$ to $O(N)$ by the FMM is achieved when N is sufficiently large and a hierarchical multi-level multipole expansion is used. In the current paper, we show a study of the accuracy of the FMM compared to the Biot-Savart law when applied to the Trefftz plane simulation, which is shown to be a very sensitive non-linear problem where accuracy is a critical factor to avoid spurious instabilities. The analysis discusses the effects of time marching method, time step, level of refinement of the FMM, number of particles in the discretization and the balance between near and far-field computational costs. The DVM-FMM algorithm is also employed to solve the temporal evolution in a shear-layer with periodic boundary conditions.

Richard, H. and Raffel, M.

"VISUALIZATION OF VORTICAL STRUCTURES BY DENSITY GRADIENT DETECTION"

Proceedings of PSFVIP-3, March 2001, Maui, Hawaii.

Applications of an advanced schlieren technique, in the following referred to as Background Oriented Schlieren or synthetic schlieren, are presented. Three experimental studies have been carried out to investigate compressible vortices. Beside other things, those vortices play a major role in the blade vortex interaction phenomena, which leads to the typical impulsive noise at helicopters. Therefore, two experiments have been performed to investigate details of the vortex formation from blade tips of two different helicopters in flight: an Eurocopter BK117 and a large US utility helicopter. Simultaneous measurements of the velocity and density fields have then been conducted to characterize the structure of compressible vortices. The background oriented schlieren appears to well complement other optical techniques like shadowgraphy or focussing schlieren methods and yield additional quantitative information. Furthermore, in the case of helicopter aerodynamics, this technique allows the effect of Reynolds number on vortex development from blade tips to be studied in full-scale flight tests more easily than using laser-based techniques.

Richard, H., Becker, W., Loose, S., Thimm, M., Bosbach, J. and Raffel, M.

"APPLICATION OF PARTICLE IMAGE VELOCIMETRY UNDER CRYOGENIC CONDITIONS"

20th International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF), Aug. 2003, pp. 393-398

Cryogenic investigations of the trailing vortices of large future transport aircrafts have been performed on an aircraft half-model with different wing tip devices. The model has been installed in the cryogenic wind tunnel (KKK) of the German-Dutch wind tunnels (DNW) in Cologne. During the tests, PIV flow field measurements have been performed in addition to conventional force, moment, and pressure distribution measurements. The measurements of the velocity field gave an insight into important aerodynamic effects as, for example, the dependents of vortex strength with changing angles of incidence as well as the differences in the spatial vorticity distribution in the wake. The PIV technique offers special advantages for the investigation of those wakes at very low temperatures, but also yields to special experimental difficulties, which are also described in this article.

Richard, H., Bosbach, J., Henning, A., Raffel, M., Willert, C. and van der Wall, B. G.

"2C AND 3C PIV MEASUREMENTS ON A ROTOR IN HOVER CONDITION"

13th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Paper No. 1122, Lisbon, Portugal, June 2006

To investigate the development of blade tip vortices under different rotor conditions like thrust and rotational speed, both two- and three-component PIV measurements were performed on a 40 percent Mach scaled Bo105 model rotor in hover condition. The vortices were traced from their creation at the

trailing edge of the blade up to half a revolution behind the blade with azimuth steps between 1 to 10 degrees at different spatial resolutions. In addition, a sequence of three-component measurements was performed just after the vortex creation at finer azimuth steps of 0.056 degrees to generate a three-dimensional volumetric data set of the blade tip vortex. The influence of the PIV image analysis parameters on the vortex parameters derived, in particular sampling window size and window overlap, has been investigated.

Richard, H., Raffel, M., Rein, M., Kompenhans, J. and Meier, G. E. A.

"DEMONSTRATION OF THE APPLICABILITY OF A BACKGROUND ORIENTED SCHLIEN (BOS) METHOD"

10th International Symposium on Applications of Laser Techniques in Fluid Mechanics, July 2000, Lisbon, Portugal.

A novel measurement technique based on the refractive index variation in a compressible flow field is presented. This concept is referred to as 'Background Oriented Schlieren' (BOS) method in the following. The differences between BOS and other optical techniques which it can best be compared with, will be discussed. Already the first results illustrate an encouraging prospect for the future applicability of this technique. The BOS method offers the capability of qualitative and quantitative investigations of unsteady density fields in high speed flows, combustion, and full-scale flight tests. The underlying principle is briefly described and an extension to a three-dimensional quantitative technique by using multiple cameras is outlined. The experimental studies which have been carried out to investigate a supersonic jet, a turbulent flame, and the blade tip vortices of a BK117 helicopter in hover flight will be presented.

Richard, H., Van der Wall, B. G., Raffel, M. and Thimm, M.

"APPLICATION OF PIV TECHNIQUES FOR ROTOR BLADE TIP VORTEX CHARACTERIZATION"

New Results in Numerical and Experimental Fluid Mechanics VI, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 96, 2008, pp. 446-453.

To investigate the development of blade tip vortices under different rotor conditions like thrust and rotational speed, both 2C and 3C PIV measurements were performed on a 40% Mach scaled Bo105 model rotor in hover condition. The vortices were traced from the trailing edge of the blade up to half a revolution behind the blade with azimuth steps between 1 to 10 degrees and different spatial resolutions. In addition, a sequence of three-component measurements was performed just after the vortex creation at finer azimuth steps of 0.056 degrees to generate a 3D volumetric data set of the blade tip vortex. The influence of the PIV image analysis parameters on the vortex parameters derived - in particular sampling window size and window overlap -- has been investigated. The measurements presented are part of the HOTIS (HOVer Tip vortex Structure) project.

Richardson, S., Bettel, J. and Holloway, A. G. L.

"DEVELOPMENT OF A TRAILING VORTEX FORMED WITH SPANWISE TIP BLOWING"

2005 ASME Fluids Engineering Division Summer Meeting and Exhibition, FEDSM2005-77130, June 2005, Houston, TX

Trailing vortices were formed with strong core jets and high turbulence levels in a wind tunnel using a NACA 0015 rectangular semi-span wing having a full span aspect ratio of 5 and a chord Reynolds number of 100,000. The jet on the vortex core was generated by air blown from the wing tip through small holes arranged along the periphery of the wing cross-section. Experiments covered a wide range of tip jet blowing rates for a wing incidence of 5 degrees. Measurements of mean velocity, mean vorticity and turbulence kinetic energy were made up to 32 chords downwind using a hot wire probe. At zero wing incidence the flow was observed to have the form of a jet in cross-flow with counter-rotating streamwise vortices of zero net circulation and a very high turbulence level. With the wing at incidence, the tip vortex envelopes the jet and as it develops its diameter grows and the jet velocity and circumferential velocity decline sharply. Further downwind the vortex formed with tip jets evolves into an axisymmetric form like a natural vortex but with a diameter up to 5 times larger. The turbulence intensities measured on the core without blowing were approximately 2.5% of the free stream velocity while with blowing they were approximately 15% in the near wake and approximately 9% in the far wake.

Richwine, D. M., Curry, R. E. and Tracy, G. V.

"A SMOKE GENERATOR SYSTEM FOR AERODYNAMIC FLIGHT RESEARCH"

NASA-TM-4137, January 1989, NASA Dryden Flight Research Center, Edwards, CA

A smoke generator system was developed for in-flight vortex flow studies on the F-18 high alpha research vehicle (HARV). The development process included conceptual design, a survey of existing systems, component testing, detailed design, fabrication, and functional flight testing. Housed in the forebody of the aircraft, the final system consists of multiple pyrotechnic smoke cartridges which can be fired simultaneously or in sequence. The smoke produced is ducted to desired locations on the aircraft surface. The smoke generator system has been used successfully to identify vortex core and core breakdown locations as functions of flight condition. Although developed for a specific vehicle, this concept may be useful for other aerodynamic flight research which requires the visualization of local flows.

Rico-Cusi, F. and Plassman, G.

"EXPECTED CAPACITY GAINS AND REDUCTION IN DELAYS FROM A WAKE VORTEX ADVISORY SYSTEM USING A PARAMETRIC MODEL OF THE WAKE VORTEX BEHAVIOR AS A FUNCTION OF ACTUAL WEATHER MEASUREMENTS"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

NASA Langley Research Center is developing a Concept of Operations for a Wake Vortex Advisory System (WakeVAS). It is known that current wake-safe aircraft spacing is conservative based on worst case conditions. Wake behavior is influenced by an airport's local meteorological environment and under favorable conditions for wake demise or advection the current aircraft spacing requirements could be reduced. To create a model of wake behavior, the Aircraft Vortex Spacing System (AVOSS) wake prediction code demonstrated at Dallas in 2000 was modified. The AVOSS wake prediction algorithm requires as input vertical profiles of wind, temperature, and turbulence. These weather data profiles were collected by a dedicated instrumentation suite at the AVOSS deployment and during a previous field deployment in Memphis. Automated Surface Observation System (ASOS) data, reported at one-minute intervals, is available at most major airports in the U.S. Wind and temperature vertical profiles can be approximated with meteorological theory from this surface data, but turbulence, measured statistically as Eddy Dissipation Rate (EDR), requires high frequency (approximately 10 Hz) wind measurements and cannot be inferred directly from one-minute surface data. A multi-variate statistical analysis was performed to establish correlation between the ASOS inputs and the AVOSS measured EDR. The output from the wake-prediction model includes time-varying (typical 30-minute resolution) reduced aircraft spacing tables. This reduced spacing data was used, along with data derived from simulation using recorded aircraft trajectories and an analysis of the traffic mix at 12 selected U.S. airports, to quantify the expected airport capacity gains. A queuing network model of the U.S. National Airspace System (NAS) was used to obtain an estimate of the delay reductions at individual airports, the overall potential NAS wide delay reduction and consequent benefit to airline operators and passengers that would be expected due to the increased capacity. This presentation describes the development of the parametric model of wake behavior, use of the model to generate reduced aircraft separations and the use of this data in the analysis of the expected capacity gains and delay reductions.

Riddick, S. E. and Hinton, D. A.

"AN INITIAL STUDY OF THE SENSITIVITY OF AIRCRAFT VORTEX SPACING SYSTEM (AVOSS) SPACING SENSITIVITY TO WEATHER AND CONFIGURATION INPUT PARAMETERS"

NASA TM-2000-209849, January 2000, NASA Langley Research Center, Hampton, VA

A study has been performed on a computer code modeling an aircraft wake vortex spacing system during final approach. This code represents an initial engineering model of a system to calculate reduced approach separation criteria needed to increase airport productivity. This report evaluates model sensitivity toward various weather conditions (crosswind, crosswind variance, turbulent kinetic energy, and thermal gradient), code configurations (approach corridor option, and wake demise

definition), and post-processing techniques (rounding of provided spacing values, and controller time variance).

Riley, J. R. and Edwards, A. S.

"AIRBORNE INSECTS AS POTENTIAL SOURCES OF ACOUSTIC REFLECTIVITY"

Journal of Atmospheric and Oceanic Technology, Vol. 14, June 1997, pp. 538-542.

Laboratory measurements of the acoustic backscattering cross sections of a variety of insects at 3.4 kHz are reported. The authors argue from these data, and from what is known (from radar studies) about insect concentrations in the lower atmosphere, that acoustic returns from insects may seriously contaminate sodar data. They suggest that this possibility should be carefully considered when interpreting backscatter coefficient data acquired in acoustic sounding experiments.

Rinehart, S. A.

"STUDY OF MODIFICATION OF ROTOR TIP VORTEX BY AERODYNAMIC MEANS"

RASA-70-02, January 1970, Rochester Applied Science Associates, Rochester, NY

The analytical investigation shows that it should be possible to significantly alter the characteristics of the trailing tip vortex for all flight conditions in a beneficial manner by injecting an airstream directly into the forming tip vortex. Analytical expressions were developed for the initial and final states of the vortex to evaluate the effects of mass flow injection on the vortex strength, swirl velocity distribution, vortex core pressure, vortex core size, and the induced drag on the blade.

Rinehart, S. A.

"EFFECTS OF MODIFYING A ROTOR TIP VORTEX BY INJECTION ON DOWNWASH VELOCITIES, NOISE, AND AIRLOADS"

J. American Helicopter Society, Vol. 16, No. 4, October 1971, pp. 48-5.

Numerous research efforts have been conducted by different investigators to alter the characteristics of the tip vortex generated by a helicopter blade to alleviate the blade-vortex interaction problem as well as the noise problem associated with impulsive loading. The present analytical investigation shows that it should be possible to significantly alter the characteristics of the trailing tip vortex for almost all flight conditions in a beneficial manner by injecting an airstream directly into the forming tip vortex. Analytical expressions were developed for the initial and final status of the vortex to evaluate the effects of mass flow injection on the vortex strength, swirl velocity distribution, vortex core pressure, and vortex core size.

Rinehart, S. A., Balcerak, J. C. and White, Jr., R. P.

"AN EXPERIMENTAL STUDY OF TIP VORTEX MODIFICATIONS BY MASS FLOW INJECTION"

RASA-71-01, January 1971, Rochester Applied Science Assoc., Rochester, NY

An experimental program was conducted to investigate the modifications of a tip vortex which could be obtained by injecting the core of a tip vortex with a stream of air. Wind tunnel tests of an airfoil model were conducted. The results obtained from flow-visualization studies, balance data and vortex-meter measurements show how the strength of the tip vortex can be reduced significantly by the injection of a linear mass flow of air into the core of the tip vortex.

Ringley, C. J., Lin, Y.-L. and Brown, Z. G.

"THE DEVELOPMENT OF A BOUNDARY LAYER TURBULENCE DATABASE FOR WAKE VORTEX APPLICATIONS"

AIAA Paper No. 2007-287, Reno, NV, January 2007

This paper describes results from extensive validation of wake-vortex environmental simulations at the Dallas Fort-Worth International Airport (DFW) against observations taken using the Aircraft Vortex Observing and Spacing System (AVOSS) during the 17-20 September 1997 field campaign. The effect of horizontal and vertical grid spacing, initialization time, and formulation of characteristic mixing length scales within the newly developed Terminal-Area PBL Prediction System-2 (TAPPS-2) are detailed. Results from the validation simulations were then used to develop an appropriate TAPPS-2 modeling configuration for a limited terminal-area mesoscale climatology at St. Louis-Lambert International Airport for the July-December 2004 period. Preliminary results, with emphasis on statistical quantities and analysis are discussed for wake-vortex forecasting applications from a mesoscale model.

Rinoie, K. and Kwak, D. Y.

"STUDIES ON VORTEX FLAPS HAVING DIFFERENT HINGE-LINE POSITIONS"

Journal of Aircraft, Vol. 38, No. 2, March-April 2001, pp. 396-398,

In this note the effect of flap hinge-line positions over the performance of the leading-edge vortex flaps has been discussed. Differences of the vortex flap hinge-line position affect the performance of the vortex flap. The best L/D ratio is attained when the delta wing has vortex flaps with a relatively small spanwise length. The formation of leading-edge separation vortex over the wing is suppressed at relatively low angle of attack, even when the vortex flap with only a small spanwise length is deflected.

Rinoie, K. and Shirotake, M.

"VORTEX BEHAVIORS OF ROLLED SUPERSONIC TRANSPORT CONFIGURATION WITH LEADING-EDGE FLAPS"

Journal of Aircraft, Vol. 43, No. 6, November-December 2006, pp. 1904-1913.

Wind tunnel measurements were done to investigate the effect of leading-edge flaps on the rolling moment characteristics of the cranked arrow wing for the supersonic transport. Static rolling moment measurements, flow visualization studies, and crossflow velocity measurements by a particle image velocimetry were made at $Re = 62,000$. Static rolling moment measurements confirmed linear restoring moment at angles of attack less than 16 deg for the models both with and without flap deflection. When the outboard leading-edge flap is deflected 12 deg, rolling moment hysteresis is observed at the roll angle of about 20 deg and angle of attack about 20 deg. The experimental results indicate that the hysteresis is caused by different vortex breakdown behaviors on the inboard wing when the wing is rotated in the clockwise and counterclockwise directions.

Risso, F., Corjon, A. and Stoessel, A.

"DIRECT NUMERICAL SIMULATION OF TRAILING VORTICES IN HOMOGENEOUS TURBULENCE"

AIAA Paper No. 1996-0802, Reno, NV, January 1996

Among the various meteorological parameters acting on the lifespan of the wake vortices, the atmospheric turbulence is one of major importance. Direct numerical simulations are one of the best tools to study turbulence even if the Reynolds number used in the computations is far below the Reynolds number of the phenomenon. Respecting as much as possible the scales of the real flow field, namely the integral length scale of atmospheric turbulence and the r.m.s. velocity, phenomena explaining the decay and the lifetime of trailing vortices are studied. It is shown in this paper that the interaction between the vortices and the ambient turbulence creates ring of vorticity through a tridimensional mechanism. The first effect of these rings is to generate axial velocities as great as the velocities induced by the vortices. Furthermore, the vortices are curved and the vortex pair could become unstable.

Risso, F., Corjon, A. and Stoessel, A.

"DIRECT NUMERICAL SIMULATIONS OF WAKE VORTICES IN INTENSE HOMOGENEOUS TURBULENCE"

AIAA Journal, Vol. 35, No. 6, June 1997, pp. 1030-1040

Three-dimensional direct numerical simulations of a vortex pair placed in an homogeneous turbulent field are presented. The phenomenon of interaction between the vortices and the turbulence is analyzed in detail from two simulations calculated on a 1353 nodes mesh grid (one case with axial core velocity, the other without). The results show that the role of large and small turbulent eddies can be separated into two independent mechanisms. The large structures are stretched by velocity gradients induced by the vortex pair. That leads to the formation of both tubes of vorticity spinning azimuthally around each vortex and associated axial velocity sheets. These structures cause a strong decrease of the maximal velocity and the curvature of the vortices. These deformations induced by the turbulence initiate an antisymmetric long-wave instability of the pair, which will probably lead to the collapse of the vortices. Concurrently, the small structures can enhance the diffusion of the vorticity out of the

vortex core. From this analysis and scale considerations, the correct form for a model of decay of the vortices is derived. On the other hand, nine simulations on a 813 nodes mesh grid are used to determine the sensibility of the results to the random turbulent initial conditions.

Rist, U.

"VISUALIZATION AND TRACKING OF VORTICES AND SHEAR LAYERS IN THE LATE STAGES OF BOUNDARY-LAYER LAMINAR-TURBULENT TRANSITION"

AIAA Paper 2012-0084, January 2012, Nashville, TN.

The purpose of this contribution is to present some examples for the use of recent data processing and visualization techniques for the study of unsteady vortical flows. The basic idea is to extract vortices, shear layers and data defining their current state from DNS data and to track their evolution in time. Some apparent signatures which help to get additional insight into the flow dynamics have been identified. They demonstrate the promising features of the technique, albeit further studies are necessary to complete this work.

Rivoalen, E., Huberson, S. and Bratec, H.

"PARTICLE SIMULATION OF SWIRLING FLOWS"

Flow, Turbulence and Combustion, Vol. 72, 2004, pp. 69-90

The vortex particle method has been applied to the axisymmetric swirling flow of a viscous fluid. The formulation used yields two transport equations which have been solved within the Lagrangian framework of particle method. The diffusion operator for both equations has been approximated by means of a Particle Strength Exchange scheme. Applications to the cases of one isolated vortex ring and two co-rotating vortex rings illustrate the interest of this new method. Special attention has been devoted to the vorticity production resulting from the interaction between the azimuthal components of vorticity and velocity. The generation of small eddies at the boundary of the vortex ring cross-section has been particularly investigated.

Rizzetta, D. P.

"NUMERICAL SIMULATION OF VORTEX INDUCED OBLIQUE SHOCK-WAVE DISTORTION"

AIAA Paper No. 96-0039, January 1996, Reno, NV.

Steady high Reynolds number supersonic flowfields were generated numerically to simulate the interaction of a streamwise wing-tip vortex with an oblique shock wave which forms above a wing surface. Solutions were obtained by time integration of the three-dimensional compressible mass-averaged turbulent Navier-Stokes and Euler equations, corresponding to both vortices and shock waves of varying strength. Effects of turbulence were accounted for by a two-equation closure model which included low-Reynolds number terms and a compressibility correction. Details of the computations are

summarized, and grid resolution and damping coefficient studies are provided to establish accuracy of the numerical results. Features of the flowfields, including vortex breakdown, are discussed, and comparison is made with experimental data in terms of shadowgraph images, static pressure distributions on the wing surface, and the trajectory of the vortex core.

Rizzetta, D. P.

"NUMERICAL INVESTIGATION OF SUPERSONIC WING-TIP VORTICES"

AIAA Paper No. 1995-2282, San Diego, CA, June 1995

Steady high-Reynolds-number flowfields about a finite-span rectangular wing mounted upright in a supersonic stream were generated numerically to investigate formation of the tip vortex. Solutions were obtained by integration of the time-dependent three-dimensional compressible Euler and mass-averaged thin-layer laminar and turbulent Navier-Stokes equations. In the turbulent case, a two-equation (k-epsilon) closure model was employed, which included low-Reynolds-number terms and a compressibility correction. Details of the computations are summarized, and a grid resolution study is provided to assess the accuracy of the numerical results. Comparison is made between the solutions of the respective governing equations, as well as with experimental data in terms of the pressure and Mach number component distributions through the center of the vortex core.

Rizzetta, D. P.

"NUMERICAL SIMULATION OF OBLIQUE SHOCK-WAVE/VORTEX INTERACTION"

AIAA Journal, Vol. 33, No. 8, August 1995, pp. 1441-1446

High Reynolds number supersonic flowfields were generated numerically by integration of the time-dependent three-dimensional compressible Euler and mass-averaged Navier-Stokes equations to simulate the interaction of a streamwise vortex with an oblique shock wave. The vortex develops at the tip of a vortex-generating fin which is suspended from the ceiling of a wind tunnel. Downstream, an oblique shock wave is produced by a wing surface which spans the width of the wind tunnel and has a two-dimensional sharp leading-edge wedge as its airfoil section. Grid resolution studies are provided to assess accuracy of the solutions. Resultant features of the numerical flowfields are discussed, and comparison is made with experimental data in terms of static pressure distributions on the wing surface.

Rizzetta, D. P.

"NUMERICAL SIMULATION OF VORTEX-INDUCED OBLIQUE SHOCK-WAVE DISTORTION"

AIAA Journal, Vol. 35, No. 1, 1997, pp. 209-211

The interaction between a streamwise wing-tip vortex and an oblique shock wave is examined using computational fluid dynamics. Solutions to the compressible three-dimensional mass-averaged

turbulent Navier-Stokes equations were solved with a two-equation turbulence closure model. For weaker interactions than those presented here, which did not result in vortex breakdown, calculations agreed reasonably well with the data. When shock induced vortex breakdown occurred, the numerically simulated interaction was not as strong as the experimental counterpart. This deficiency is attributed to the inability of the turbulent Navier-Stokes equations to accurately simulate formation of the tip vortex. In particular, it has been shown that the turbulence model could not reproduce the experimentally measured wake like axial Mach number profile, which is considered to be crucial to vortex breakdown in this case. Numerical reproduction of strong tip-vortex/shock-wave interaction thus appears to be limited by lack of adequate turbulence modeling for such flows at high Reynolds numbers.

Rizzetta, D. P.

"NUMERICAL INVESTIGATION OF SUPERSONIC WING-TIP VORTICES"

AIAA Journal, Vol. 34, No. 6, June 1996, pp.1203-1208.

Steady high-Reynolds-number flowfields about a finite-span rectangular wing mounted upright in a supersonic stream were generated numerically in order to investigate formation of the tip vortex. Solutions were obtained by integration of the time-dependent three-dimensional compressible Euler and thin-layer laminar and mass-averaged thin-layer laminar and turbulent Navier-Stokes equations. In the turbulent case, a two-equation (k -epsilon) closure model was employed, which included low-Reynolds-number terms and a compressibility correction. Details of the computations are summarized, and a grid resolution study is provided to assess the accuracy of the numerical results. Comparisons are made between solutions of the various governing equations, as well as with experimental data in terms of the pressure and Mach-number component distributions in the vortex core.

Robasky, F. M. and Clark, D. A.

"WIND FORECAST ALGORITHM FOR WAKE MITIGATION FOR DEPARTURES (WTMD): BASELINE ALGORITHM DESCRIPTION AND PERFORMANCE SUMMARY"

Report 43PM Wx-0105, July 2008, MIT Lincoln Lab., Lexington, MA

Wake Turbulence Mitigation for Departures (WTMD) is a developmental FAA system to safely reduce wake-related departure wait times for airports with closely spaced parallel runways. It will apply to aircraft following departures of Heavy Jets or B757s on the adjacent runway if a crosswind exists sufficient to prevent transport of a wake from the leading wake-generating aircraft into the adjacent runway departure's path. A crucial component of this system is a wind forecast algorithm (WFA) developed at MIT Lincoln Laboratory, to determine when such winds will persist for a sufficient time period to safely implement the procedure. This document serves two purposes: 1) to describe the operation and logic of the WFA in detail, down to the level of its constituent functions, and 2) to characterize WFA performance and accuracy, largely based on special verification data gathered at St. Louis Lambert International Airport and Houston George Bush Intercontinental Airport.

Robasky, F. M. and Clark, D. A.

"A WIND FORECAST ALGORITHM TO SUPPORT WAKE TURBULENCE MITIGATION FOR DEPARTURES (WTMD)"

88th AMS Annual Meeting, New Orleans, LA, January 2008

A conceptually simple, reliable, high-update model of future runway-specific crosswinds has been developed to provide an indication of anticipated wind conditions favorable for WTMD procedures. It is expected that the use of these reduced aircraft separation standards will provide a substantial reduction in wake vortex related delay. The formal requirements of the Wind Forecast Algorithm (WFA) are to be specified in early 2008, for subsequent certification and implementation. This baseline WFA, and the experience gained in its development, evaluation, and implementation will also serve as a platform for an approach to mitigating wake vortex related spacing delays for the arrival portion of the overall problem. This is expected to be more challenging, as it involves a domain of concern that is spatially much larger and temporally much longer, due to the need to safely and efficiently manage aircraft approaches to the runways.

Roberts, C. L.

"FLIGHT TEST ANALYSIS OF THE FORCES AND MOMENTS IMPARTED ON A B737-100 AIRPLANE DURING WAKE VORTEX ENCOUNTERS"

M.S. Thesis, March 1999, Howard University, Washington, DC

Aircraft travel has become a major form of transportation. Several of our major airports are operating near their capacity limit, increasing congestion and delays for travelers. As a result, the National Aeronautics and Space Administration (NASA) has been working in conjunction with the Federal Aviation Administration (FAA), airline operators, and the airline industry to increase airport capacity without sacrificing public safety. One solution to the problem is to increase the number of airports and build new runways; yet, this solution is becoming increasingly difficult due to limited space. A better solution is to increase the production per runway. This solution increases the possibility that one aircraft will encounter the trailing wake of another aircraft. Hazardous wake vortex encounters occur when an aircraft encounters the wake produced by a heavier aircraft. This heavy-load aircraft produces high-intensity wake turbulence that redistributes the aerodynamic loads of trailing smaller aircraft. This situation is particularly hazardous for smaller aircraft during takeoffs and landings. To gain a better understanding of the wake-vortex/aircraft encounter phenomena, NASA Langley Research Center conducted a series of flight tests from 1995 through 1997. These tests were designed to gather data for the development of a wake encounter and wake measurement data set with the accompanying atmospheric state information. This data set is being compiled into a database that can be used by wake vortex researchers to compare with experimental and computational results. The purpose of this research is to derive and implement a procedure for calculating the wake-vortex/aircraft interaction portion of that database by using the data recorded during those flight tests. There were three objectives to this research. Initially, the wake-induced forces and moments from each flight were

analyzed based on varying flap deflection angles. The flap setting alternated between 15 and 30 degrees while the separation distance remained constant. This examination was performed to determine if increases in flap deflection would increase or decrease the effects of the wake-induced forces and moments. Next, the wake-induced forces and moments from each flight were analyzed based on separation distances of 1-3 nautical miles. In this comparison, flap deflection was held constant at 30 degrees.

Roberts, C. L., Vicroy, D. D. and Smith, S. T.

"FLIGHT TEST ANALYSIS OF THE FORCES AND MOMENTS IMPARTED ON A B737-100 AIRCRAFT DURING WAKE VORTEX ENCOUNTERS"

AIAA Paper No. 2000-3980, Denver, CO, August 2000

Several of our major airports are operating at or near their capacity limit, increasing congestion and delays for travelers. As a result, the National Aeronautics and Space Administration (NASA) has been working in conjunction with the Federal Aviation Administration (FAA), airline operators, and the airline industry to increase airport capacity and safety. As more and more airplanes are placed into the terminal area the probability of encountering wake turbulence is increased. The NASA Langley Research Center conducted a series of flight tests from 1995 through 1997 to develop a wake encounter and wake-measurement data set with the accompanying atmospheric state information. The purpose of this research is to use the data from those flights to compute the wake-induced forces and moments exerted on the aircraft. The calculated forces and moments will then be compiled into a database that can be used by wake vortex researchers to compare with experimental and computational results.

Roberts, L.

"ON WAKE VORTEX ALLEVIATION"

The Future of Aeronautics, Kansas Univ., 1974, pp. 139-167

Research within NASA relating to the nature of lift-induced vortex wakes behind large aircraft and the means whereby the hazard they represent to smaller aircraft can be alleviated is reviewed. The research, carried out in ground-based facilities and in flight shows that more rapid dispersion of the wake can be affected by several means and that the modification of span-loading by appropriate flap deflection holds promise of early practical application.

Roberts, T. W. and Murman, E. M.

"A COMPUTATIONAL METHOD FOR HELICOPTER VORTEX WAKES"

AIAA Paper No. 1984-1554, Los Angeles, CA, June 1984

A method for calculating the wake geometry and blade loads for a hovering helicopter rotor is presented. The approach incorporates a simplified free wake model of the rotor in a finite difference calculation of the flow field. Calculations showing the effect of vortex core size and the number of vortex filaments representing the wake are presented.

Robins, R. E. and Delisi, D. D.

"MODELING CROSSWIND SHEAR EFFECTS IN NASA'S AVOSS PREDICTION ALGORITHM"

AIAA Paper No. 2006-1076, Reno, NV, January 2006.

A method for including crosswind shear effects in APA, NASA's trailing vortex prediction algorithm, is described. The method is based on an approximation to the evolution equation for axial vorticity. Results from a new model based on the method are compared with field data for two cases from the Memphis vortex-observation field experiment run in August 1995 by NASA, using a continuous wave lidar built by MIT's Lincoln Laboratory. The model is run in predictive and diagnostic mode to improve trajectory predictions, measurements of the crosswind profile, and estimates of circulation decay.

Robins, R. E. and Delisi, D. P.

"3-D NUMERICAL SIMULATIONS OF TRAILING VORTEX EVOLUTION"

AIAA Paper No. 2006-1079, Reno, NV, January 2006.

A new method for solving the 3-D Navier-Stokes equations is described. The key feature of the method is a form of the eddy viscosity, developed by F. Holzapfel, that goes to zero in regions of intense rotation such as the core of a trailing vortex. The method permits the specification of vertically varying ambient current (or wind) and stratification, and uniform ambient turbulence. Comparisons between model results and observations are shown for laboratory-scale and full-scale trailing vortex flows.

Robins, R. E. and Delisi, D. P.

"MODELING OF ATMOSPHERIC EFFECTS ON WAKE VORTICES"

9th Conf. on Aviation, Range, and Aerospace Meteorology, Paper 7.11, AMS, Orlando, FL, September 2000

When instrument flight rules (IFR) are required due to poor visibility, aircraft are required to remain a minimum distance behind the preceding aircraft, with the result that airport capacity can be adversely affected. In certain atmospheric conditions (e.g., strong cross winds), this minimum distance is greater than it needs to be for safe operations. If it could reliably be determined when minimum following distances can be reduced, then airport capacity during IFR could be increased. We have developed an approach to modeling the evolution of aircraft wake vortices which can be used to predict the length of time that wake vortices will remain a hazard to following aircraft. In this approach, atmospheric

conditions are represented by vertical profiles of potential temperature, cross wind, and turbulence. Either eddy dissipation rate (EDR) or turbulence kinetic energy (TKE) can be used to characterize the turbulence. The wake vortices are characterized by their initial position, lateral separation, and initial descent speed. The model has been used by the NASA Langley Research Center as the predictor component in a prototype system (called AVOSS for Aircraft Vortex Spacing System) that could be used by air traffic control to determine when it is acceptable to reduce aircraft spacing. In this paper, we describe our modeling approach and show examples of how various atmospheric conditions can be expected to affect the evolution of aircraft wake vortices.

Robins, R. E. and Delisi, D. P.

"NWRA AVOSS WAKE VORTEX PREDICTION ALGORITHM VERSION 3.1.1"

NASA/CR-2002-211746, June 2002, Northwest Research Associates, Bellevue, WA.

This report provides a detailed description of the wake vortex prediction algorithm used in the Demonstration Version of NASA's Aircraft Vortex Spacing System (AVOSS). The report includes all equations used in the algorithm, an explanation of how to run the algorithm, and a discussion of how the source code for the algorithm is organized. Several appendices contain important supplementary information, including suggestions for enhancing the algorithm and results from test cases.

Robins, R. E. and Delisi, D. P.

"POTENTIAL HAZARD OF AIRCRAFT WAKE VORTICES IN GROUND EFFECT WITH CROSSWIND"

J. Aircraft, Vol. 30, No. 2, Mar.-Apr. 1993, pp. 201-206.

Aircraft wake vortices, evolving close to the ground in a crosswind, are a potential hazard to aircraft landing or taking off on the same or parallel runways. The objective of this work has been to study, by means of numerical simulation, the effect of aerodynamic and environmental conditions on the generation and transport of these vortices. The approach has been to use a computer code which solves the two-dimensional, time-dependent, incompressible Navier-Stokes equations expressed in stream function-vorticity form, to study wake vortices in ground effect with crosswind. The code permits the specification of arbitrary atmospheric stability and wind profiles. A mixed no-slip/free-slip lower boundary condition has been invoked to model the interaction of the vortices with the ground. Comparisons of code output with laboratory and field data have been used to validate the code. Simulation results have shown that, even after evolution times and cross-runway transport distances on the order of 3 min and 500 m, vortices generated by large aircraft close to the ground in a crosswind can carry sufficient average circulation to be a potential hazard to smaller aircraft. Additional full-scale data need to be acquired and additional numerical comparisons need to be performed to assess the significance of these new results.

Robins, R. E. and Delisi, D. P.

"3-D CALCULATIONS SHOWING THE EFFECTS OF STRATIFICATION ON THE EVOLUTION OF TRAILING VORTICES"

In *Computation of Three-Dimensional Complex Flows*, Notes on Numerical Fluid Mechanics, Vol. 53, Eds. Deville et al., Vieweg, Braunschweig, 1996

We have computed numerical solutions to the 3-D Navier-Stokes equations for a stratified, incompressible fluid. Our results show that stratification significantly modifies the phenomena that occur during the vertical migration and linking instability of trailing vortices. In particular, we show that stratification accelerates the development of the linking instability and suppresses the vertical migration of the trailing vortices.

Robins, R. E. and Delisi, D. P.

"NUMERICAL SIMULATIONS OF THREE-DIMENSIONAL TRAILING VORTEX EVOLUTION"

AIAA Journal, Vol. 35, No. 9, September 1997, pp. 1552-1555.

We have computed solutions that depict the evolution of trailing vortices, from initially having their axes slightly perturbed from parallel, through the early stages of perturbation growth, to the occurrence of linking, followed by the formation and migration of rings. Our results agree with the findings of Crow, the most significant of which is that the wavelength of maximum perturbation growth for vortices undergoing linking instability is initially about 8.6 times the initial distance between the parallel vortices. In addition, our results extend Crow's analysis by showing that linking occurs sooner for vortices with tighter cores, the maximum growth wavelength decreases as the instability evolves, and the angle of growth of the maximum perturbation evolves from around 48 degrees predicted by Crow to near 65 degrees at the time of linking. Finally, results for vortices composed of a superposition of components having different wavelengths show good agreement with laboratory results.

Robins, R. E. and Delisi, D. P.

"EFFECTS OF STRATIFICATION ON 3-D TRAILING VORTEX EVOLUTION"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 185-201

Two studies are presented. First, the effects of stratification on Crow instability are examined numerically. Results from calculations for Froude number, F , equal to 2, 4, and 8, are shown at non-dimensional times of 4, 6, 8, and 10. Stratification is seen to accelerate the onset of linking due to Crow instability and to suppress the downward migration of the vortices. It is also seen that for low stratification, such that $F > \text{about } 8$, Crow instability results in the formation of downward propagating vortex rings. For higher stratification, such that $F < \text{about } 4$, the ring formation is suppressed. In a second study, laboratory and numerical results, in good agreement, show the occurrence of a small-scale instability for strong stratification, such that $F < \text{about } 2$. These results may be relevant to airport

operations because of the possibility that stratification effects and small-scale instabilities may result in trailing vortices remaining near the flight path of following aircraft.

Robins, R. E. and Delisi, D. P.

"NUMERICAL SIMULATION OF THREE-DIMENSIONAL TRAILING VORTEX EVOLUTION IN STRATIFIED FLUID"

AIAA Journal, Vol. 36, No. 6, June 1998, pp. 981-985

Numerical solutions to the Navier-Stokes equations that depict the evolution of a trailing vortex pair descending in stratified, incompressible fluid are presented. Both three-dimensional and two-dimensional results are shown for the Froude numbers 1, 2, 4, and 8 and infinity. For three and two dimensions, the results indicate that stratification, through generation of countersign vorticity, causes the separation between the vortices to decrease and, through buoyancy forces, suppresses the vertical migration of the vortices. In three dimensions, Crow instability causes the vortices eventually to link and to form rings when the Froude number is greater than or equal to 4, and the rate at which the linking and ring formation occur is greater for higher stratification (lower Froude number). The formation of rings is suppressed, however, for stratification so high that the Froude number is less than or equal to 2.

Robins, R. E. and Delisi, D. P.

"NUMERICAL STUDY OF VERTICAL SHEAR AND STRATIFICATION EFFECTS ON THE EVOLUTION OF A VORTEX PAIR"

AIAA Journal, Vol. 28, No. 4, April 1990, pp. 661-669

The objective of this study is to investigate with a numerical model how coexisting vertical shear and stratification affect the evolution of a vortex pair. Our results show that the Richardson number (the ratio of stratification forces to shear forces) is an important parameter in the evolution. When the Richardson number is large, the vortex pair evolves symmetrically, the left and right vortex decaying equally, or nearly equally, rapidly. In this case, the effect of the shear is small, and stratification dominates the evolution. When the Richardson number is sufficiently small, however, the evolution is dramatically different. Under these conditions, the vortices evolve asymmetrically, and the vortex with rotational sense opposite to that of the mean shear decays while the vortex with the same rotational sense as the mean shear survives. This 'solitary vortex' then decays slowly with time. The transition from solitary to nonsolitary vortex evolution occurs over Richardson numbers between 0.5 and 4 for the Froude number range 0.5 to 4.0.

Robins, R. E. and Delisi, D. P.

"FURTHER DEVELOPMENT OF A WAKE VORTEX PREDICTOR ALGORITHM AND COMPARISONS TO DATA"

AIAA Paper No. 1999-0757, Reno, NV, January 1999.

Recent enhancements have been made to a fast (less than 0.1 sec per case on a state-of-the-art workstation) algorithm that predicts wake vortex transport and decay. The turbulence decay term has been improved, and turbulent kinetic energy (TKE) profiles are now used instead of constant TKE values to represent the ambient turbulence. A database approach has been adopted to quantify comparisons between algorithm predictions and measurements of wake vortex transport and decay. The use of databases to optimize the constant factor, k , in the term governing the effect of turbulence on vortex decay is reported, with the result that k appears to depend on the intensity of ambient turbulence. Several comparisons of algorithm predictions with collections of data are presented, and agreement between predictions and measurements is shown to be reasonably good. Measured circulation decay is shown to be consistent between data sets collected at Memphis and Dallas-Fort Worth, and linear (with time) bounds on the decay are estimated.

Robins, R. E. and Delisi, D. P.

"NUMERICAL SIMULATIONS OF VORTEX EVOLUTION"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

If it were possible to determine when aircraft separation standards imposed by the hazard due to trailing vortices could safely be reduced, then airport capacity could be increased. An important step in being able to realize this possibility is the development of reliable methods for predicting the effect of realistic atmospheric conditions on the behavior of trailing vortices. In this talk, we describe two prediction methods, one based on solving the equations describing fluid motion and the other based on solving equations derived from a heuristic analysis of vortex evolution. Predictions from both methods are compared with full-scale observations and the comparisons are shown to be favorable. We conclude that useful predictions of trailing vortex evolution are feasible and may be useful in the effort to increase airport capacity.

Robins, R. E., and Delisi, D. P.

"EFFECT OF GROUND INTERACTION ON TRAILING VORTEX EVOLUTION"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000.

Lidar observations of position and circulation of trailing vortices generated within 50m of the ground, from NASA deployments at MEM, DFW and JFK airports, are studied to determine the effect of ground interaction on vortex evolution. The data suggest that circulation decay in ground effect is independent of ambient conditions and is approximately bounded by $G/G_0 = 1 - T/8$, where G is circulation, G_0 is initial circulation and T is time normalized by b/V , where b is initial vortex separation and V is initial vortex descent speed. Predictions by engineering models of vortex evolution in ground effect are compared with observations. The models are evaluated by quantifying comparisons of vertical position and circulation decay for over one hundred cases.

Robins, R. E., and Delisi, D. P.

"WAKE VORTEX ALGORITHM SCORING RESULTS"

NASA/CR-2002-211745, June 2002, Northwest Research Associates, Bellevue, WA.

This report compares the performance of two models of trailing vortex evolution for which interaction with the ground is not a significant factor. One model uses eddy dissipation rate (EDR) and the other uses the kinetic energy of turbulence fluctuations (TKE) to represent the effect of turbulence. In other respects, the models are nearly identical. The models are evaluated by comparing their predictions of circulation decay, vertical descent, and lateral transport to observations for over four hundred cases from Memphis and Dallas/Fort Worth International Airports. These observations were obtained during deployments in support of NASA's Aircraft Vortex Spacing System (AVOSS). The results of the comparisons show that the EDR model usually performs slightly better than the TKE model.

Robins, R. E., Delisi, D. P. and Greene, G. C.

"DEVELOPMENT AND VALIDATION OF A WAKE VORTEX PREDICTOR ALGORITHM"

AIAA Paper No. 1998-0665, Reno, NV, January 1998.

The algorithm described herein predicts the trajectories and circulation decay of aircraft trailing vortices. We first present the methodology used by the algorithm to simulate trailing vortex behavior, including (i) the descent of vortices through a realistic atmosphere defined by stratification, turbulence, and cross wind profiles, and (ii) the interaction of the vortices with the ground. Both the increase in separation between the vortices caused by their approaching the ground and the generation of secondary vorticity due to their interaction with the ground are modeled by the algorithm. We then compare algorithm results with field data and discuss the algorithm's validity and sensitivity. We show that the algorithm performs reasonably well for vortices out of ground effect, and produces promising results for vortices in ground effect. Since it runs in less than one-tenth of a second on a state-of-the-art workstation, the algorithm is suitable for use in a real-time aircraft vortex separation system.

Robins, R.E., Delisi, D. P. and Greene, G. C.

"ALGORITHM FOR PREDICTION OF TRAILING VORTEX EVOLUTION"

Journal of Aircraft, Vol. 38, No. 5, September-October 2001, pp. 911-917.

We describe an algorithm that predicts the trajectories and circulation decay of aircraft trailing vortices. We first present the methodology used by the algorithm to simulate trailing vortex behavior, including 1) the descent of the vortices through a realistic atmosphere defined by crosswind, turbulence, and stratification profiles and 2) the interaction of the vortices with the ground. Examples are presented to demonstrate the algorithm's capability. We then describe a database approach for quantifying comparisons between algorithm predictions and measurements of wake vortex transport

and decay. The use of databases to optimize the constant factor k in the term governing the effect of turbulence on vortex decay is reported, with the result that k appears to depend on the intensity of ambient turbulence. Using selected groupings of cases from the database, we have determined that vortices not interacting with the ground decay about a factor of two faster in high-intensity ambient turbulence than in low-intensity ambient turbulence. We also show that the circulation decay for vortices in the ground effect appears to be independent of the ambient turbulence level.

Robinson, A. and Hunter-Tod, J. H.

"BOUND AND TRAILING VORTICES IN THE LINEARISED THEORY OF SUPERSONIC FLOW, AND THE DOWNWASH IN THE WAKE OF A DELTA WING"

R. & M. No. 2409, March 1952, Aeronautical Research Council, Great Britain.

The field of flow round a flat airfoil at incidence can be regarded in linearized theory as the result of both bound and trailing vortices for supersonic as well as for low-speed flight. This leads to a convenient method, given the lift distribution over an airfoil, for calculating the flow round it at supersonic speeds. As an application of the results the downwash is calculated in the wake of a delta wing lying within the Mach cone emanating from its apex. The downwash is found to be least just aft the trailing edge and is everywhere less than the downflow at the airfoil. It increases steadily to a limiting value which is attained virtually within two chord lengths of the trailing edge. The ratio of the downwash at any point in the wake to the downflow at the airfoil decreases with increasing Mach number and apex angle.

Robinson, A. and Hunter-Tod, J. H.

"BOUND AND TRAILING VORTICES IN THE LINEARIZED THEORY OF SUPERSONIC FLOW, AND THE DOWNWASH IN THE WAKE OF A DELTA WING"

Report No. 10, October 1947, Cranfield Institute of Technology, Cranfield, Bedford, UK.

The field of flow round a flat airfoil at incidence can be regarded in linearized theory as the result of both bound and trailing vortices for supersonic as well as for low-speed flight. This leads to a convenient method, given the lift distribution over an airfoil, for calculating the flow round it at supersonic speeds. As an application of the results the downwash is calculated in the wake of a delta wing lying within the Mach cone emanating from its apex. The downwash is found to be least just aft the trailing edge and is everywhere less than the downflow at the airfoil. It increases steadily to a limiting value which is attained virtually within two chord lengths of the trailing edge. The ratio of the downwash at any point in the wake to the downflow at the aerofoil decreases with increasing Mach number and apex angle.

Robinson, B. A., Barnett, R. M. and Agrawal, S.

"A SIMPLE NUMERICAL CRITERION FOR VORTEX BREAKDOWN"

AIAA Paper No. 1992-0057, Reno, NV, January 1992

Vortex breakdown is currently identified in numerical flow solutions through post-processing techniques. Although these methods can identify breakdown accurately, they need to be simplified and their cost reduced for practical aircraft design use. Therefore, a simple Rossby number criterion is proposed. The criterion is established using solutions to Euler and Navier-Stokes equations for low-speed flow over a flat plate delta wing at high angles of attack. Comparison with experimental data shows consistent values of Rossby number at breakdown. The proposed Rossby number criterion provides an efficient means of locating breakdown in numerical solutions. It is also straightforward to incorporate in any flow solver.

Robinson, G. H. and Larson, R. R.

"A FLIGHT EVALUATION OF METHODS FOR PREDICTING VORTEX WAKE EFFECTS ON TRAILING AIRCRAFT"

NASA TN D-6904, November 1972, NASA Flight Research Center, Edwards, CA

The results of four current analytical methods for predicting wing vortex strength and decay rate are compared with the results of a flight investigation of the wake characteristics of several large jet transport aircraft. An empirical expression defining the strength and decay rate of wake vortices is developed that best represents most of the flight-test data. However, the expression is not applicable to small aircraft that would be immersed in the vortex wake of large aircraft.

Robinson, J. J.

"A SIMULATION-BASED STUDY OF THE IMPACT OF AIRCRAFT WAKE TURBULENCE WEIGHT CATEGORIES ON AIRCRAFT CAPACITY"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 22-1 to 22-15

The Federal Aviation Administration (FAA) is considering revising the current aircraft wake turbulence weight categories and the associated separation standards during IMC. Various proposals have been submitted to the FAA regarding this revision. This paper presents the results and conclusions of a capacity study conducted by The Boeing Company. This study examined the impact of these proposed changes on airport capacity during instrument meteorological conditions (IMC). The approach taken for this study was to simulate arrival and departure operations at ten major US airports by employing a database derived from the 1993 Official Airline Guide traffic schedule. Simulations were conducted for the traffic mix at each airport utilizing one standard, representative runway configuration. The aircraft wake vortex separation requirements were changed to model various proposed weight categories; these separations were then applied to the traffic set at each airport. In general, it was found that current capacity levels would be reduced by as much as 4%.

Robinson, P. A.

"WAKE VORTEX DETECTION AND REPORTING SYSTEM"

US Patent 8,135,500 B1, March 2012.

A method for estimating the effect of environmental conditions on an aircraft, including measuring the motions of an aircraft, estimating the expected motions of the aircraft, wherein the expected motions of an aircraft are estimated using information regarding the aircraft's control inputs and/or control surface positions; and estimating, based on the measured motions of the aircraft and the expected motions of the aircraft, the forces exerted on the aircraft by the environmental conditions, wherein the forces are estimated based on a difference between the measured motions of the aircraft and expected motions of the aircraft.

Rocklage-Marliani, G., Schmidts, M. and Vasanta Ram, V. I.

"THREE-DIMENSIONAL LASER-DOPPLER VELOCIMETER MEASUREMENTS IN SWIRLING TURBULENT PIPE FLOW"

Flow, Turbulence and Combustion, Vol. 70, 2003, pp. 43-67

The present work is an experimental study of the evolution characteristics of swirl in the flow in a pipe at a moderately high Reynolds number and over a wide range of swirl numbers characterizing the swirl strength. The measurements are done by 3D LDV in a specially designed facility that works on the principle of refractive-index matching. Swirl with the well-defined distribution of a constant angular velocity is introduced into the test section of this facility by a swirl generating device in which a tube bundle in the pipe rotates about the pipe axis. The measurements have been processed to yield the mean-velocity vector and the Reynolds stress tensor in this flow. An analysis of the measured evolution characteristics brings out a dominant effect of swirl with a solid body rotation as the annihilation of Reynolds shear stresses.

Rockwell, D.

"VORTEX-BODY INTERACTIONS"

Ann. Rev. Fluid Mechanics, Vol. 30, 1998, pp. 199-229

Interaction of a vortex, or combinations of them, with a cylinder, blade, or foil may involve both rapid distortion of the incident vorticity field and shedding of vorticity from the surface of the body. This review focuses on the underlying flow physics, with the aim of clarifying the origin of the induced loading. In the case of near or direct encounter of the incident vortex, the relation between three-dimensional features of the flow structure and the local loading poses interesting challenges for further research. With recently developed simulation and laboratory techniques, opportunities now exist to determine the instantaneous quantitative structure of these complex distortions and to interpret them within a theoretical, vorticity-based framework. Effective control of vortex interactions appears to be

attainable. It will be necessary, however, to develop creative strategies, distinct from those traditionally employed for control of unstable shear flows.

Rodenhiser, R. J.

"AN ULTRASONIC METHOD FOR AIRCRAFT WAKE VORTEX DETECTION"

M.S. Thesis, August 2005, Worcester Polytechnic Institute, Worcester, MA.

This thesis documents the experimental proof of concept study for an ultrasonic method of wake vortex detection. A new acoustic technique is utilized to measure the circulation produced in the wake of lift-generating aircraft. Ultrasonic signals are transmitted in a path around the wake vortex, and are used to determine the average in-line velocity component along the acoustic path. It is shown herein that this velocity component is directly proportional to the net circulation value within the acoustic path. This is the first study to take this methodology and implement it in a realistic airport setting. This project included constructing a prototype and conducting field tests to prove the validity of this technology in a realistic environment setting. During field tests an acoustic path enclosed the vorticity shed behind one wing of a Piper PA-28 aircraft. Fourteen initial test flights were conducted in calm atmospheric conditions, and results show circulation values measured are comparable in magnitude and direction to expected circulations generated by the Piper PA-28 aircraft. Additional testing in various atmospheric conditions revealed the scope of practice for such a measurement technology. This study demonstrates the validity of the acoustic method in detecting aircraft wake vortices. Future investigations and applications utilizing this technique are discussed within.

Rodenhiser, R. J., Durgin, W. W. and Johan, H.

"ULTRASONIC METHOD FOR AIRCRAFT WAKE VORTEX DETECTION"

Journal of Aircraft, Vol. 44, No. 3, May-June 2007, pp. 726-732

This paper describes the experimental proof of concept study for an ultrasonic method of wake vortex detection for airport use. This new acoustic method utilizes travel time of acoustic pulses around a closed path to measure the net circulation within the acoustic path. In this application the closed path encloses the vorticity shed from one side of a Piper PA-28 aircraft wing. Magnitude and sign of circulation detected is comparable to the expected circulation generated by the Piper PA-28 test aircraft. This study demonstrates the validity of the acoustic method in detecting aircraft wake vortices. Further investigations and applications utilizing this technique are discussed.

Rodenhiser, R. J., Durgin, W. W. and Johari, H.

"ACOUSTIC TECHNOLOGY FOR AIRCRAFT WAKE VORTEX DETECTION"

Proceedings of the Twelfth Conference on Aviation Range and Aerospace Meteorology, American Meteorological Society, Atlanta, Georgia, Feb. 2006

National research efforts over the past two decades have focused on developing a wake vortex detection technology that could be deployed in an airport setting for real-time wake vortex hazard assessment. Recent research has proven a new acoustic method of wake vortex detection that has been successful in initial field trials at detecting the presence of wake vortex circulations (Rodenhiser, 2005). This paper discusses how this new technology can be utilized to determine the strength and location of wake vortices in the airport terminal area.

Rodoni, C. A.

"AN INVESTIGATION OF THE FLOW PARAMETERS OF A CONFINED TURBULENT VORTEX"

M.S. Thesis, September 1969, Mass. Institute of Technology, Cambridge, MA

The object of this paper is to find out to what extent laminar vortex models can be adjusted by means of empirically derived 'effective eddy viscosity' terms to describe turbulent vortices; and to look directly for empirical correlations for the characteristic flow parameters. A literature search was conducted to obtain the empirical data, and a computer program was written to determine its dependence on the appropriate dimensionless parameters. Although the observed vortex flow patterns are shown to agree with theory, it is found that the 'eddy viscosity' approach to predicting the angular momentum dissipation is not very satisfactory.

Rodriguez, S. B., Espinoza, F. A., Steinberg, S. L., and El-Genk, M. S.

"TOWARDS A UNIFIED SWIRL VORTEX MODEL"

AIAA Paper No. 2012-3354, June 2012, New Orleans, LA.

A review of the literature shows the existence of dozens of single-cell, axisymmetric, Newtonian-fluid vortices that, in one form or another, are solutions to the Navier-Stokes Equation. However, little research has been conducted in the literature to investigate common traits that are shared by these vortices. This research lays out a foundation of common mathematical traits, with a focus on the azimuthal velocity v . Notwithstanding their diverse mathematical and physical origin, it can be shown that these vortices are diverse manifestations of a single vortex family -- they are united by a set of at least seven common mathematical traits. As a first common trait, we show that there are only four possible categories of single-cell, axisymmetric, Newtonian-fluid vortices. Next, by normalizing and overlaying the vortices into a single figure, three additional traits are noted, namely that $v(r=0) = 0$; they have similar azimuthal velocity profiles; and the azimuthal velocity is asymmetric about r . Thereafter, a fifth trait is noted by doing a series expansion for the azimuthal velocity of each vortex (as found in the literature), and expressing it as an alternating series that expands geometrically with odd exponents (truncated Laurent series with real coefficients). Finally, two more traits are noted by taking limit bounds for each series, thus showing that one bound is the Rankine (solid body) vortex, and the other is a Lamb-Oseen sine-like bound. In brief, we note that the vortices have seven traits in common, and hereby propose that these vortices are essentially diverse manifestations of a single vortex family.

Roe, P.

"VORTICITY CAPTURING"

AIAA Paper 2001-2523, June 2001, Anaheim, CA.

The paper identified one of the most important algorithm development areas to be three dimensional flows with strong vorticity. The importance of the area of research is illustrated by pointing out the general form of the vorticity transport equation involves vorticity transport, diffusion by viscosity and generation by barotropic mechanism. Therefore, a robust algorithm is one that would be able to properly address these vorticity driven physics. Vortex methods, hybrid, vorticity confinement techniques were highlighted and briefly reviewed, followed by illustrations of the spurious features that can result in the various computational schemes. Some initial ideas on attacking these issues have been proposed.

Roelen, A. L. C., Molemaker, R. J., Piers, R., Hayes, P., Joyce, A., Graham, G.

"A COST BENEFIT ANALYSIS OF WAKE VORTEX MEASURES: DEMONSTRATION OF THE ASTER APPROACH FOR SETTING AND OPTIMISING SAFETY TARGETS"

NLR-CR-2001, National Aerospace Laboratory, Amsterdam, The Netherlands

ASTER stands for 'Aviation Safety Targets for Effective Regulation'. It is a project carried out on behalf of DG-TREN of the European Commission in 2000-2001. The objective of ASTER is to develop a method to set and optimize safety targets to achieve the optimum level of safety for the aviation system by distributing the safety burden more evenly among the different actors. This includes the development of a method for cost benefit analysis to assess safety benefits of any change, including changes in legislation and rulemaking, in relation to the costs of implementing those changes. As a demonstration of the ASTER approach for setting and optimizing safety targets, a case study was conducted on wake vortex measures.

Roesch, P. and Dequin, A.-M.

"EXPERIMENTAL RESEARCH ON HELICOPTER FUSELAGE AND ROTOR HUB WAKE TURBULENCE"

Journal of American Helicopter Society, Vol. 30, Issue 1, 1985, pp. 43-51.

Various flow visualization experiments (ranging from hydrodynamic tests of small models to tuft and smoke tests conducted on wind tunnel models and full-scale aircraft in flight) show that large eddy structures are convected periodically in the wake generated by helicopter rotor hubs. Spectral analysis of hot film flow signals reveals that discrete energy components are added to the continuous (turbulent) energy spectrum, not only at the integer multiples of the blade passage frequency, but also at every rotor harmonic frequency. Moreover, it is shown that the ratio of discrete/turbulent energy at rotor harmonic frequencies is uniquely determined by the advance ratio. Similar results are found concerning the unsteady air loads on the stabilizers. Some explanations concerning tail-shake

phenomena are given, based on the spectral analysis of wake signals and fin bending stresses, and solutions are suggested to alleviate the problem.

Rogberg, P. and Dritschel, D. G.

"MIXING IN TWO-DIMENSIONAL VORTEX INTERACTIONS"

Physics of Fluids, Vol. 12, No. 12, December 2000, pp. 3285-3288

We examine the mixing of a passive tracer initially contained within several widely separated vortex patches in a two-dimensional, nearly inviscid, incompressible flow. The initial vortex positions and sizes are chosen so that they collapse toward a common center, resulting in a strong interaction. The area of tracer ejected from the vortices is found to be well correlated with the departure of each tracer contour from an ideal elliptical shape. This result appears to be more widely applicable, and, in particular, it may be useful for quantifying small-scale mixing in realistic atmospheric and oceanic flows.

Rogers, A. L., Henson, W. L. W. and Manwell, J. F.

"SODAR WIND RESOURCE MEASUREMENT RESULTS AT FALMOUTH, MA"

Letter Report, September 2005, Renewable Energy Research Laboratory, University of Massachusetts, Amherst, MA.

SODAR data have been collected at the Falmouth wastewater treatment plant in the spring of 2005 by the Renewable Energy Research Laboratory at the University of Massachusetts at Amherst. The data were collected to estimate the wind resource for possible wind turbines and to determine the wind shear characteristics at the site. Some of the data was determined to be corrupted but good data was collected at several heights during the month of June, 2005. Based on these data, the wind shear at the site can be modeled by exponential fit with a coefficient of 0.33 and the mean annual wind speed at 70 m is most likely between 5.88 and 6.36 m/s.

Rogers, A. W.

"APPLICATION OF TWO-DIMENSIONAL VORTEX THEORY TO THE PREDICTION OF FLOW FIELDS BEHIND WINGS OF WING-BODY COMBINATIONS AT SUBSONIC AND SUPERSONIC SPEEDS"

NACA TN-3227, September 1954, Langley Aeronautical Lab., Langley Field, VA

A theoretical investigation has been made of a general method for predicting the flow field behind the wings of plane and cruciform wing and body combinations at transonic or supersonic speeds and slender configurations at subsonic speeds. The wing trailing-vortex wake is represented initially by line vortices distributed to approximate the spanwise distribution of circulation along the trailing edge of the exposed wing panels. The afterbody is represented by corresponding image vortices within the body. Two-dimensional line-vortex theory is then used to compute the induced velocities at each vortex and the resulting displacement of each vortex is determined by means of a numerical stepwise

integration procedure. The method was applied to the calculation of the position of the vortex wake and the estimation of downwash at chosen tail locations behind triangular-wing and cylindrical-body combinations at supersonic speeds. The effects of such geometric parameters as aspect ratio, angle of attack and incidence, ratio of body radius to wing semi-span, and angle of bank on the vortex wake behind wings of wing-body combinations were studied. The relative importance of wing vortices, the corresponding image vortices within the body, and body crossflow in determining the total downwash was assessed at a possible tail location. It was found that the line-vortex method of this report permitted the calculation of vortex paths behind wings of wing-body combinations with reasonable facility and accuracy. A calculated sample wake shape agreed qualitatively with one observed experimentally, and sample results of the line-vortex method compared well with an available exact crossflow-plane solution. An empirical formula was derived to estimate the number of vortices required per wing panel for a satisfactory computation of downwash at tail locations. It was found that the shape of the vortex wake and the ultimate number of rolled-up vortices behind a wing depend on the circulation distribution along the wing trailing edge. For the low-aspect-ratio plane wing and body combinations considered, it appeared that downwash at horizontal tail locations is largely determined except near the tail-body juncture by the wing vortices alone for small ratios of body radius to wing semispan, and by the body upwash alone for large values of that ratio.

Rogers, A. W.

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Rogers, L. C. and Kididis, A. S.

"PARACHUTE/VORTEX INTERACTION STUDY, INITIAL WIND TUNNEL AND DROP TESTING"

AIAA Paper 1997-1479, June 1997, San Francisco, CA.

The multi-ship airdrop mission produces the probability of paratroopers encountering the vortices of aircraft in preceding positions. The basic physics and an analysis method was developed to assess the comparative risk level for any given formation. The basic physics were investigated using scaled parachute testing. The result of the testing indicated that a vectorial analysis of the computed path of a jumper in proximity to a vortex would be the only available analytical method for assessing risk. Testing was performed using two scale model parachutes of the T-10 type used by U.S. Army paratroopers. The testing consisted of vertical wind tunnel testing and drop testing in proximity to a simple dynamic pressure generator. Results show that the gradient of dynamic pressure exposure is the primary mechanism of parachute collapse. The three-dimensional path of the paratrooper is also key to vortex encounter risk.

Rogers, M.

"A REVIEW OF AFOSR EFFORTS IN WAKE TURBULENCE"

Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, Air Force Flight Dynamics Laboratory, AFFDL-TM-75-16-FGC, 1974, p. 71

A summary is given of the wake turbulence topics which have interested the Air Force Office of Scientific Research. These topics included vortex formation and decay and the way they affect Air Force operations, the effect of viscosity on vortex aerodynamics, and the relationship between span loading and vortex characteristics. Possible future applications of the basic vortex understanding gained were suggested: improved control and performance using vortex technology (use of canard surfaces to control separation over a swept wing), use of helicopter wakes to disperse fog or pollutants, effect of fatigue failure, and the possible coupling of aircraft wakes in the generation of gravity waves.

Rohne, E.

"EXPERIMENTAL INVESTIGATION OF THE ROLLUP OF THE UNSTABLE SHEET OF DISCONTINUITY BEHIND A WING OF FINITE SPAN"

Zeitschrift fur Flugwiss, Vol. 5, No. 12, December 1957, pp. 365-370

The length over which the trailing vortex sheet is rolled up into two vortex cores and the distance between the rolled-up vortices have been investigated experimentally for a rectangular and a trapezoidal wing with GP-387 airfoil sections, each with the wing tips sharp and rounded off. [In German.

Rokhsaz, K.

"A BRIEF SURVEY OF WING TIP DEVICES FOR DRAG REDUCTION"

SAE Paper No. 932574, September 1993, Anaheim, CA.

A short survey of wing tip geometries for drag reduction is presented. These devices have been divided into two broad categories of passive and active. The first category is made of fixed geometries, while the second group is made of those employing moving parts. The former group is further divided into planar and nonplanar designs. In every case, a brief explanation of the underlying logic is given. Altogether, more than fifteen completely different designs and over seventy references have been cited. Some of these designs, such as winglets, have been explored for many years and have proven to be very effective at reducing the induced drag at higher values of lift coefficient. Some others, such as wing tip turbines, have just begun to attract attention. Wing tip fuel tanks, not being solely employed for drag reduction, have not been included in this paper.

Rokhsaz, K. and Kliment, L. K.

"FEASIBILITY OF MODELING WAKE VORTICES IN GROUND EFFECT IN A WATER TUNNEL"

SAE 2005-01-3360, Aerotech Congress, October 2005, Grapevine, TX

An experiment is performed to investigate the feasibility of using a water tunnel to study the aircraft wake vortex behavior in ground effect. Two blades are used to generate the vortices, simulating an aircraft wake. The ground plane is modeled with a splitter plate. Vortex mean positions are determined using an optical technique. The results show all the critical properties of an aircraft wake in the vicinity of the ground. The vortices are shown to descend monotonically until they start interacting with the ground plane. The minimum height to which the filaments sink is shown to compare favorably with that predicted by numerical methods and the operational data obtained from lidar. The vortex span is shown to increase at the same rate as that estimated from an empirical model based on lidar data as well. Vortex rebound is observed with maximum heights comparing well with other predictions. Partial comparison is also presented with a numerical scheme developed for AVOSS application. These observations all seem to favor a water tunnel as an appropriate means of investigating this type of flow field.

Rokhsaz, K. and Kliment, L. K.

"A BRIEF SURVEY OF THE EXPERIMENTAL METHODS USED FOR WAKE VORTEX INVESTIGATIONS"

SAE Paper No. 2007-01-3788, September 2007, Los Angeles, CA

Some of the methods used for experimental detection and examination of wake vortices are presented. The aim of the article is to provide the reader a brief overview of the available methods. The material is divided into two major sections, one dealing with methods used primarily in the laboratory, and the second part devoted to those used in field operations. Over one hundred articles are cited and briefly discussed.

Rokhsaz, K. and Kliment, L. K.

"EXPERIMENTAL INVESTIGATION OF CO-ROTATING VORTEX FILAMENTS IN A WATER TUNNEL"

Journal of Aircraft, Vol. 40, No. 6, Nov.-Dec. 2003, pp. 1115-1122

The dynamic behavior of co-rotating vortex filaments is investigated in a water tunnel. Comparisons are made between the motion of a single filament and that resulting from interactions between two filaments. Correlation is observed visually between the merger location and the vortex strength. In most cases, vortex merger is shown to occur within one orbit. Quantitative data is presented on the variations of the vortex span, the amplitude of motion, the spiraling rate, and the center of spiraling, all as functions of downstream distance. It is shown that the vortex span does not vary considerably except in cases where the interactions among the filaments are strong. The amplitude of motion is shown to be much larger than that of a single vortex, while growing with downstream distance. Furthermore, the amplitude of motion is shown to exhibit a preferred direction in some cases. The presented data reveals that in the two-vortex cases, the spiraling rate is nearly constant. It is also shown that despite considerable motion of the filaments, the center of spiraling does not deviate significantly from a straight line.

Rokhsaz, K. and Miller, T. S.

"THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE SELF-INDUCED OSCILLATIONS OF A SINGLE VORTEX FILAMENT"

AIAA Paper No. 2002-3304, St. Louis, MO, June 2002

A simple analytical model, consistent with that of Crow, is used to explore the self-induced oscillations of a single longitudinal vortex filament. The new model is based on the Biot and Savart law and results in an eigenvalue problem for the wavenumber of the first bending mode. Following the method of Crow, the singularity at the lower limit of the Biot and Savart integrals is removed by introducing a cutoff distance that is related to the core radius. It is proven that the first bending mode of the vortex filament is composed of a sinusoidal shape, which cannot be of an arbitrary wavenumber. A concise expression is derived for the associated wavenumber, which is shown to be very different from those of Kelvin waves. The results from the Kelvin's analysis and the present model are compared with a limited amount of previously obtained experimental data. Close agreement is shown between one of the dominant frequencies in the experimental data and that of the present formulation.

Rokhsaz, K. and Rebours, R.

"QUANTITATIVE MEASUREMENTS OF WAKE VORTEX MOTION IN A WATER TUNNEL"

AIAA Paper No. 2001-0111, Reno, NV, January 2001

The paper presents a novel technique for quantitative data acquisition regarding the motion of a pair of vortex filaments in a water tunnel. This technique allows measuring the vortex strength, the oscillation frequency of the vortex filaments, and the rate of growth of their amplitudes simultaneously. The filaments are visualized using dye injection while their cross sections are illuminated with light sheets at different downstream locations and recorded. Time history of the vortex position is extracted from these recordings. This measurement technique is shown to be a viable method of analyzing wake vortex motion. Pairs of vortex filaments, typical of those wingtips, are used in a water tunnel to demonstrate the application of the method. Vortex strength and the distance between the filaments are varied independently and the motions of the vortex pairs are quantified. The method is shown to be robust and reliable, as long as the dye remains in the vortex core.

Rokhsaz, K., Foster, S. R. and Miller, L. S.

"EXPLORATORY STUDY OF AIRCRAFT WAKE VORTEX FILAMENTS IN A WATER TUNNEL"

J. Aircraft, Vol. 37, No. 6, November-December 2000, pp. 1022-1027

The objective of this work is to examine the meandering nature of a single vortex filament. The flow field is typical of that in the vicinity of an aircraft wing tip vortex. Self-induced motion of the vortex filament is examined within the confines of potential flow theory and is compared with experimentally obtained data. A single-sensor constant temperature anemometer is used to obtain the experimental data for comparison. Data is presented that shows the variation of the core radius with distance downstream of the point of origin as a function of the vortex strength. Also, experimental data is presented to show the variation in the amplitude of wandering downstream of the point of origin.

Rokhsaz, K., Rebours, R. and Foster, S. R.

"QUANTITATIVE MEASUREMENTS OF WAKE VORTEX MOTION IN A WATER TUNNEL"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 862-867

A novel technique is presented for quantitative data acquisition regarding the motion of a pair of vortex filaments in a water tunnel. This technique allows measuring the vortex strength, the oscillation frequency of the vortex filaments, and the rate of growth of their amplitudes simultaneously. The filaments are visualized using dye injection while their cross sections are illuminated with light sheets at different downstream locations and recorded. Time history of the vortex position is extracted from these recordings. This measurement technique is shown to be a viable method of analyzing wake vortex motion. Pairs of vortex filaments, typical of those of wingtips, are used in a water tunnel to

demonstrate the application of the method. Vortex strength and the distance between the filaments are varied independently, and the motions of the vortex pairs are quantified. The method is shown to be robust and reliable, as long as the dye remains in the vortex core.

Rom, J.

"VORTEX FLOWS AND THE ROLLED-UP VORTEX WAKE"

In: High Angle of Attack Aerodynamics, Chapter 5, Springer-Verlag, New York, 1992, pp. 131-149.

The trailing vortex wake behind the lifting wing is an excellent example of the natural tendency of free vortical shear layers to roll up into well-defined concentrated vortices with the essentially inviscid outer flow rotating around an inner viscous core. Such is the case when the well-known tip vortices are established in the wake of high AR lifting wings. High speed computers provide the means for calculating the characteristics of the complete flow field over the wing as well as its wake and the rolled-up tip vortices. These calculations will be presented and discussed in the following chapters. However, before diving into the details of the calculations, it is of particular interest and importance to gain some insight into the flow field over wings and their wakes. This can best be done by examining analytical solutions, such as those developed by Spreiter and Sacks, to the problems of simulating the main features of the rolled-up vortex flow.

Rom, J. and Zorea, C.

"THE CALCULATION OF THE LIFT DISTRIBUTION AND THE NEAR VORTEX WAKE BEHIND HIGH AND LOW ASPECT RATIO WINGS IN SUBSONIC FLOW"

TA-168, January 1973, Technion-Israel Inst. of Technology, Haifa, Israel

A method is presented for the combined calculation of the lift and lift distribution on a wing and of the trailing vortex flow behind the wing. It is assumed that the lift of a wing is generated by a system of vortices distributed over the complete wing planform and shed away from each elemental area on the planform. Using the concepts of the vortex lattice method, it is assumed in the linear lift variation case, that the vortices are aligned on the wing planform and are shed away from the trailing edges. Vortex line interaction calculations for the trajectories of the vortex lines are programmed. As a result, the leading-edge lift vortices which are obtained on slender wings can now be handled. This report contains a description of the numerical method.

Rom, J., Almosnino, D. and Zorea, C.

"CALCULATION OF THE NON LINEAR AERODYNAMIC COEFFICIENTS OF WINGS OF VARIOUS SHAPES AND THEIR WAKES, INCLUDING CANARD CONFIGURATIONS"

ICAS 1978, September 1978, Lisbon, Portugal.

This paper introduces a method for the calculation of the non linear, longitudinal aerodynamic characteristics of various planar shapes, including multiple lifting surface configurations in subsonic flow, at high angles of attack. The method developed can handle complex planforms such as closely coupled canard-wing combinations, wing-tail combinations, cruciform types of wing arrangements, various flaps, elevators, dihedral angles as well as ground effect problems. The present work uses a modified 'Vortex Lattice Method' by including the effects of the shedding and of the development of the rolled-up wake. The solution is carried out by an iterative process, saving a lot of computing time. Comparisons with experimental data show very good agreement even in cases of very strong nonlinear effects of leading-edge vortices, or in cases of side-edge vortices rolling up above the surface of low aspect ratio wings.

Rom, J., Portnoy, H. and Zorea, C.

"INVESTIGATIONS OF THE ROLLING-UP OF THE VORTEX WAKE AND CALCULATION OF NON-LINEAR AERODYNAMIC CHARACTERISTICS OF WINGS"

AFOSR-TR-76-1146, June 1976, Technion-Israel Inst. of Technology, Haifa, Israel

This report investigates the rolling-up of vortices over and behind wings of low and high aspect ratios, and simultaneously the evaluation of the aerodynamic characteristics including the spanwise and chordwise pressure distributions on the wings. The present method is based on the extension of the Vortex Lattice concepts also to low aspect ratio wings and the rolled-up vortex which is established over as well as behind the wings. The computer program, which was developed, can reproduce the results of the Vortex Lattice Method (VLM) for linear aerodynamic coefficients for high aspect ratio wings. The wake effect is included in the modified VLM program. This wake calculation showed that the center of the tip vortex is very near the wings' tip for the high aspect ratios wings. The non-linear aerodynamic characteristics are evaluated when the vortices are shed over the wing and begin the rolling-up process from the leading edges. This effect is particularly important for wings of low aspect ratios.

Rom, J., Portnoy, H. and Zorea, C.

"INVESTIGATION INTO THE FORMATION OF WING-TIP VORTICES"

TAE-199, February 1974, Technion-Israel Inst. of Technology, Haifa, Israel

A resume of the program of theoretical investigations into wing-tip vortex formation which is now in process in the Department of Aeronautical Engineering at the Technion, Haifa is given. The work is proceeding along two separate paths which it is hoped eventually to amalgamate. The first investigation consists of numerical work on the rolling up of the wing trailing vortex system when it is represented by discrete vortices according to a series of models of increasing complexity starting from the two-dimensional elliptic distribution as originally treated by Westwater and proceeding by stages through various lifting-line and lifting surface models, including some exhibiting non-linear lift characteristics.

Rom, J., Zorea, C. and Gordon, R.

"ON THE CALCULATION OF NON-LINEAR AERODYNAMIC CHARACTERISTICS AND THE NEAR VORTEX WAKE"

International Council of the Aeronautical Sciences Paper 74-27, Haifa, Israel, 1974

Methods for the calculation of the distribution of vortices on the wing planform and on the trailing vortex wake by an iterative procedure based on the application of the vortex lattice method concept are described. In the case when the trailing vortices are taken to leave the wing at the trailing edge only, the calculation results in determining the linear aerodynamic characteristics and the shape of a rolled wake. The present investigation considers the case when the vortices for each cell are allowed to leave the wing planform at a fixed angle, and the case when the vortex shedding can be limited to the planform edge only.

Romeos, A., Giannadakis, A., Perrakis, K. and Panidis, T.

"CO-ROTATING VORTEX INTERACTION"

Aircraft Engineering and Aerospace Technology, Vol. 88, No. 2, 2016, pp. 285-293.

The purpose of this paper is to study the structure and dynamic development of a pair of co-rotating trailing vortices, during their formation, interaction and merging, using detailed experimental measurements of the velocity and vorticity fields. The vortices were generated using two half wings (NACA0030) positioned at equal and opposite angles of attack at the entrance of the test section of an open-circuit, subsonic, wind tunnel. Velocity vector measurements were obtained at $Re = 133,000$, on cross-plane grids at several distances from the trailing edges of the wings, using an in-house developed four-sensor hot wire anemometer probe. The results include cross-plane contour plots of the mean and fluctuating velocity as well as mean vorticity fields. Each of these variables is affected in a different way, providing complementary information on the development of the flow field. After shedding, the two vortices are swept along the stream-wise direction and swirl around each other, thereby developing a braid of two vortices, which then deforms the external flow field. Gradually, the interaction with the external flow field links both vortices together until the final merging and the formation of a new stable linear vortex emerges.

Romeos, A., Lemonis, G., Panidis, T. and Papallion, D. D.

"MULTISENSOR HOT WIRE VORTICITY PROBE MEASUREMENTS OF THE FORMATION FIELD OF TWO COROTATING VORTICES"

Flow Turbulence Combustion, Vol. 83, 2009, pp. 153-183.

Experimental evidence is reported, regarding the formation of a pair of co-rotating tip vortices by a split wing configuration, consisting of two half wings at equal and opposite angles of attack. Simultaneous measurements of the three-dimensional vector fields of velocity and vorticity were conducted on a cross plane at a downstream distance corresponding to 0.3 cord lengths (near wake),

using an in-house constructed 12-sensor hot wire anemometry vorticity probe. The probe consists of three closely separated orthogonal 4-wire velocity sensor arrays, measuring simultaneously the three-dimensional velocity vector at three closely spaced locations on a cross plane of the flow field. This configuration makes possible the estimation of spatial velocity derivatives by means of a forward difference scheme of first order accuracy. Velocity measurements obtained with an X-wire are also presented for comparison. In this near wake location, the flow field is dictated by the pressure distribution established by the flow around the wings, mobilizing large masses of air and leading to the roll up of fluid sheets. Fluid streams penetrating between the wings collide, creating on the cross plane flow a stagnation point and an 'impermeable' line joining the two vortex centers. Along this line fluid is directed towards the two vortices, expanding their cores and increasing their separation distance. This feeding process generates a dipole of opposite sign streamwise mean vorticity within each vortex. The rotational flow within the vortices obligates an adverse streamwise pressure gradient leading to a significant streamwise velocity deficit characterizing the vortices. The turbulent flow field is the result of temporal changes in the intensity of the vortex formation and changes in the position of the cores (wandering).

Rood, E. P.

"INTERPRETING VORTEX INTERACTIONS WITH A FREE SURFACE"

Journal of Fluids Engineering, Vol. 116, March 1994, pp. 91-94.

An understanding of the process by which vorticity interacts with a free surface is sought by analytical examination of the free-surface condition for the vorticity flux. A novel mechanism is suggested that permits closed vortex loops to evolve into open loops terminating at the free surface. It is hypothesized that abrupt vortex 'disconnection' observed in physical experiments, arises from a smooth diffusion of vorticity through the interface, with a necessary coincident tangential acceleration of the interface attributed to viscous forces.

Rood, E. P.

"VORTEX INTERACTIONS WITH A FREE-SURFACE"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 34-1 - 34-5

Free-surface phenomena are characterized by viscous processes that produce vortices of all scales. Although the processes are like those associated with solid wall boundary layers, the quite different boundary conditions distinguish the two types of flow. Recent advances in capabilities for both physical and numerical experiments as well as analytic investigations of boundary conditions have provided the means to comprehensively investigate the detailed dynamics of vortices interacting with the free-surface. An understanding of the three-dimensional interactions is important for interpreting results of laboratory scale aircraft wake studies in which an air-water free-surface is employed as a ground plane. In this paper the physical problem is the interaction between vortices in water and an air-water

interface. The term 'free surface' denotes the interface between water and air on which the shear stresses caused by the motions of the air are insignificant compared to those caused by the motion of the water. Surface contamination, when present, produces a gradient in the surface tension that results in a stress on the water. The focus of this paper is on the qualitative mechanisms underlying the observed interactions between vorticity and the free-surface, such as the apparent rebound of the vortices from the free-surface.

Rooseleer, F., Treve, V., De Visscher, I. and Graham, R.

"WAKE TURBULENCE RE-CATEGORIZATION ON APPROACH AND DEPARTURE FOR SAFE AND MORE EFFICIENT AIR TRAFFIC MANAGEMENT"

ICAS 2016, Paper ICAS-2016-0230, September 2016, Daejeon, Korea.

Current wake turbulence separation minima between successive arrival or departure air traffic are usually based on ICAO 3-category scheme (with specific minima for A380), using maximum gross weight as criterion. Possible significant efficiency optimization can be achieved from increased number of categories or establishment of aircraft pair-wise separation minima, enabling a reduction of over-conservatism for some aircraft pairs, while maintaining an acceptable safety level.

Roosenboom, E. M. W., Schroder, A., Agocs, J. and Geisler, R.

"COHERENT WAKE STRUCTURES FOR TRANSPORT AIRCRAFT AT CARGO AIRDROP CONFIGURATIONS INCLUDING PARACHUTES"

AIAA Paper 2013-2536, June 2013, San Diego, CA.

Results of two stereoscopic Particle Image Velocimetry measurement campaigns have been post-processed with the snapshot Proper Orthogonal Decomposition (POD) to identify coherent structures in the wake of a transport aircraft with its tailgate down and with and without various cargo configurations placed in the wake. These configurations are representative of generic airdrop scenarios. Coherent structures are identified in the wake of the transport aircraft with an open ramp. Periodic events are found in the wake of cargo, while including a support plate underneath the cargo suppresses the coherent structures. The influence of the trailing wake of the open ramp and its influence on the coherent wake structures in the cargo wakes are discussed. The snapshot POD also suggests that vortex shedding is present in the wake of a parachute attached to the cargo.

Roper, A. T.

"DEVELOPMENT OF AIRCRAFT VORTEX WAKES IN TURBULENT FLOW"

J. Aircraft, Vol. 6, No. 1, January-February 1969, pp. 65-66

This paper presents a method for predicting the time dependence of vortex size, strength, and peak tangential velocity in turbulent flow. The existence of a similar solution is assumed for large times and

the turbulent shearing stresses are represented in general functional form without recourse to mixing length or eddy viscosity assumptions.

Rorke, J. B. and Moffitt, R. C.

"MEASUREMENT OF VORTEX VELOCITIES OVER A WIDE RANGE OF VORTEX AGE, DOWNSTREAM DISTANCE AND FREE STREAM VELOCITY"

NASA CR-145213, July 1977, Sikorsky Aircraft, Stratford, C.

A wind tunnel test was conducted to obtain vortex velocity signatures over a wide parameter range encompassing the data conditions of several previous researchers while maintaining a common instrumentation and test facility. The generating wing panel was configured with both a revolved airfoil tip shape and a square tip shape and had a semispan aspect of 4.05/1.0 with a 121.9 cm span. Free stream velocity was varied from 6.1 m/sec to 76.2 m/sec and the vortex core velocities were measured at locations 3, 6, 12, 24 and 48 chord lengths downstream of the wing trailing edge, yielding vortex ages up to 2.0 seconds. Wing pitch angles of 6, 8, 9 and 12 deg were investigated. Detailed surface pressure distributions and wing force measurements were obtained for each wing tip configuration. Correlation with vortex velocity data taken in previous experiments is good. During the rollup process, vortex core parameters appear to be dependent primarily on vortex age. Trending in the plateau and decay regions is more complex and the mechanisms appear to be more unstable.

Rorke, J. B. and Moffitt, R. C.

"WIND TUNNEL SIMULATION OF FULL SCALE VORTICES"

NASA CR-2180, March 1973, Sikorsky Aircraft, Stratford, CT.

An experimental investigation has been conducted to determine the important scaling parameters for the flow in the core region of a vortex generated by a rectangular wing tip. The effect of an unconventional planform, the ogee tip, on the tip vortex is also determined. For rectangular planform wings, the measured vortex core diameter to chord ratios, peak tangential velocity ratios, and axial velocity ratios are shown to be functions only of wing lift coefficient and elapsed time from vortex formation, and appear to be independent of both Mach number and Reynolds number. The peak tangential velocities in the diffuse vortex generated by the ogee tip are only 25 percent of those in the vortex generated by the rectangular wing.

Rose, R. and Dee, F. W.

"AIRCRAFT VORTEX WAKES AND THEIR EFFECTS ON AIRCRAFT"

ARC Report CP-795, December 1963, Royal Aircraft Establishment, Farnborough, England. (Also, Tech. No. Aero. 2934 and ARC-5419.)

Tests have been made using a Venom traversing aircraft to determine the strength and decay, away from the ground, of vortex wakes behind Comet and Vulcan aircraft. The present tests show that the effects of an intersection at right angles to the wake reduce to a low level (less than 8 ft/sec equivalent gust) after 2 minutes. This result is unlikely to be any more severe for a transport aircraft.

Rosenberger, B. T., Charlton, E. F. and Miller, D. N.

"ADHESIVE PANELS OF MICROVANE ARRAYS FOR REDUCING EFFECTS OF WINGTIP VORTICES"

US Patent 2016/0272302 A1, September 2016.

In one embodiment, a wing includes a low-pressure side, a high-pressure side opposite the low-pressure side, and a drag reducing apparatus coupled to the low pressure using an adhesive. The drag reducing apparatus includes a first side coupled to the low-pressure side of the wing, and a second side opposite the first side, the second side comprising a plurality of vortex generators arranged in an array configuration, the array configuration of vortex generators operable to weaken a wingtip vortex generated by the wing by generating one or more vane vortices near an end of the low-pressure side of the wing.

Rosenhead, L.

"THE FORMATION OF VORTICES FROM A SURFACE OF DISCONTINUITY"

Proceedings of the Royal Society of London, Series A, Vol. 135, Issue 823, November 1931, pp. 170-192

The surface of discontinuity, which is a vortex sheet, is replaced by a distribution of finite elemental vortices along its trace, and the paths of these vortices are determined by a numerical step-by-step method. The line joining these vortices at any instant is assumed to approximate the actual shape of the surface at that time. It is shown that the effect of instability upon a surface of discontinuity of sine form is to produce concentrations of vorticity at equal intervals along the surface, and it is also shown that the surface of discontinuity tends to roll up round these points of concentration with an accompanying increase in the amplitude of the displacement.

Rosenkrans, W.

"OUTMANEUVERED AIRFLOW"

Aero Safety World, Flight Safety Foundation, February 2013, pp. 12-16.

U.S. wake vortex science safely updates approach and departure concepts essential to NextGen capacity gains.

Roshko, A.

"ON THE DEVELOPMENT OF TURBULENT WAKES FROM VORTEX STREETS"

PhD Thesis, January 1952, California Institute of Technology, Pasadena, CA.

Wake development behind circular cylinders at Reynolds numbers from 40 to 10,000 was investigated in a low-speed wind tunnel. Standard hot-wire techniques were used to study the velocity fluctuations. The Reynolds number range of periodic vortex shedding is divided into two distinct subranges. At $R = 40$ to 150 , called the stable range, regular vortex sheets are formed and no turbulent motion is developed. The range $R = 150$ to 300 is a transition range to a regime called the irregular range, in which turbulent velocity fluctuations accompany the periodic formation of vortices. The turbulence is initiated by the laminar-turbulent transition in the free layers which spring from the separation points on the cylinder. This transition first occurs in the range $R = 150$ to 300 . Spectrum and statistical measurement were made to study the velocity fluctuations. In the stable range the vortices decay by viscous diffusion. In the irregular range the diffusion is turbulent and the wake becomes fully turbulent in 40 to 50 diameters downstream. It was found that in the stable range the vortex sheet has a periodic spanwise structure. The dependence of shedding frequency on velocity was successfully used to measure flow velocity. Measurements in the wake of a ring showed that an annular vortex sheet is developed.

Roshko, A.

"ON THE DEVELOPMENT OF TURBULENT WAKES FROM VORTEX STREETS"

NACA TR-1191, 1954, Langley Aeronautical Laboratory, Langley Field, VA

Wake development behind circular cylinders at Reynolds numbers from 40 to 10,000 was investigated in a low-speed wind tunnel. Standard hot-wire techniques were used to study the velocity fluctuations. The Reynolds number range of periodic vortex shedding is divided into two distinct subranges. At $R = 40$ to 150 , called the stable range, regular vortex sheets are formed and no turbulent motion is developed. The range $R = 150$ to 300 is a transition range to a regime called the irregular range, in which turbulent velocity fluctuations accompany the periodic formation of vortices. The turbulence is initiated by the laminar-turbulent transition in the free layers which spring from the separation points on the cylinder. This transition first occurs in the range $R = 150$ to 300 . Spectrum and statistical measurement were made to study the velocity fluctuations. In the stable range the vortices decay by viscous diffusion. In the irregular range the diffusion is turbulent and the wake becomes fully turbulent in 40 to 50 diameters downstream. It was found that in the stable range the vortex sheet has a periodic spanwise structure. The dependence of shedding frequency on velocity was successfully used to measure flow velocity. Measurements in the wake of a ring showed that an annular vortex sheet is developed.

Rossier, R. N.

"A TWIST OF FATE"

Business and Commercial Aviation, September 2002, pp. 77-86

In days past, takeoffs and landings were considered the most dangerous flight regimes with respect to wake turbulence. Low, slow and near other aircraft, pilots would have little room to maneuver or recover in the event of a wake turbulence encounter, and the result could prove calamitous. While these are still the most likely times for encountering the dangerous vortices, recent research and empirical evidence suggest that wake turbulence at altitude could pose risks equal to the low-level hazards. Steps are being taken to better understand wake turbulence, and to develop strategies to avoid encounters both en route and in terminal operations.

Rossow, V.

"CLASSICAL WING THEORY AND THE DOWNWARD VELOCITY OF VORTEX WAKES"

Journal of Aircraft, Vol. 43, No. 2, March-April 2006, pp. 381-385

Classical wing theory is extended downstream from a flat vortex sheet to include vortex-wake configurations that can be considered as fully rolled up into a vortex pair. Classical wing theory was chosen as the method to be used because it is based on the flux of downward momentum imparted to the ambient flow field by the lift on a wing. After the theory is reviewed to establish the theoretical process used to analyze vortex wakes, it is extended to the configuration of lift-generated wakes that occur after roll-up of the vortex sheet, and that are composed of a vortex pair inside of an oval-shaped region that propagates downward as a unit. The distribution of downward momentum inside the oval, and in the surrounding fluid, found for the rolled-up vortex pair is then applied to vortex wakes as they undergo instabilities that lead to their decomposition and dispersion.

Rossow, V. J.

"REDUCTION OF UNCERTAINTIES IN PREDICTION OF WAKE-VORTEX LOCATIONS"

Journal of Aircraft, Vol. 39, No. 4, July-August 2002, pp. 587-596

Lift-generated vortex wakes of subsonic transport aircraft are known to pose a rolling-moment hazard to in-trail following aircraft. Hazardous wake-encounters are now avoided by maintaining in-trail separation distances that are larger than needed for other operational considerations. To increase airport capacity, considerable effort has been devoted to the development of techniques and procedures by which vortex wakes can be accurately located as a function of time so that following aircraft can avoid them with less in-trail spacings. To improve the accuracy with which vortex wakes can be located, this paper reports on a study of the uncertainties associated with the determination of the time-dependent location of vortex wakes, and on ways to reduce the uncertainties. It is found that it is beneficial to reduce the uncertainties as much as possible by application of technology currently available for aircraft guidance, and for measurement of wind velocity along the flight corridor by

aircraft. It appears however, that the growth in the size of the hazardous region surrounding wake vortices is so rapid that it currently prevents the reduction to one minute of in-trail spacings between aircraft during approach to airports. Therefore, if airport capacity is to be increased, it is concluded that it will be necessary to also introduce some other system of sequential flight corridors like the ones illustrated here; e.g., to provide more lateral and vertical distance between the flight paths of aircraft so that wake encounters are avoided.

Rossow, V. J.

"TWO-FENCE CONCEPT FOR EFFICIENT TRAPPING OF VORTICES ON AIRFOILS"

J. Aircraft, Vol. 29, No. 5, September-October 1992, pp. 847-855

Previous work on the use of a vortex trapped above a wing to produce high lift at low angles of attack is extended here. It is first postulated that the optimum way to trap a vortex is to design the airfoil section and wing so that the flow along the vortex core is minimized. It is then shown that a vertical fence both in front of and behind the separation bubble generated by the trapped vortex is an effective way to reduce the mass flow removal and its associated drag to a negligible amount. To show that vertical surfaces upstream and downstream of the vortex separation bubble have an opposite effect on the source requirements for vortex trapping, conformal mapping methods are used to obtain the solutions for a variety of simple two-dimensional, inviscid, incompressible flow configurations. Trapped-vortex flowfield solutions for the flow over flat plate and Clark-Y airfoils are then used to demonstrate that the heights of the fences can be tailored to make the required mass withdrawal (and therefore, the drag due to trapping) to be vanishingly small.

Rossow, V. J.

"EFFECT OF GROUND AND CEILING PLANES ON SHAPE OF ENERGIZED WAKES"

J. Aircraft, Vol. 31, No. 25, September-October 1994, pp. 1227-1231

Results are presented that provide insight into the structure of energized wakes in general and in the presence of ground or ceiling planes when powered-lift devices are tested at zero and low wind-tunnel velocities. It was first found that the vortex sheets (that separate the energized wake from the ambient fluid) are approximately constant in strength and move at constant velocity. This characteristic permits the use of free-streamline theory and mapping methods to obtain a solution for an energized wake in free space. It is shown that such a solution is in good agreement with those obtained with point-vortex and vortex-sheet-segment approximations for the wake edges. All three methods indicate that vortex wakes first move inboard, and sometimes also upward, before they turn and go downward, so that interference between the wake and the energizing surface is more likely. Several solutions were then presented to indicate how the presence of a nearby ground plane causes the energized wake to constrict less than when in free space. In contrast, another set of solutions indicate that the presence of a ceiling plane enhances wake constriction so that the wake width is even smaller than when in free

space. Hence, a ground plane tends to reduce the chance for interaction between the wake and the energizing elements, while a nearby ceiling plane tends to increase the likelihood for interference.

Rossow, V. J.

"VORTEX-FREE FLIGHT CORRIDORS FOR AIRCRAFT EXECUTING COMPRESSED LANDING OPERATIONS"

Journal of Aircraft, Vol. 43, No. 5, September-October 2006, pp. 1424-1428.

A factor that limits airport arrival and departure rates is the need to wait between operations for the wake vortices of preceding aircraft to decay to a safe level. As airport traffic demand increases, creative methods will be needed to overcome the limitations caused by the hazard posed by vortex wakes so that airport capacities can be safely increased. The problem addressed here is the design of vortex-free trajectories for aircraft as they fly from their cruise altitudes down to their final approach paths and to a landing. The guidelines presented recommend that the flight path of each aircraft in a group executing nearly simultaneous landings be spaced far enough apart laterally along organized flight paths so that the vortex wakes of preceding aircraft will not intrude into the airspace to be used by following aircraft. An example is presented as to how a combination of straight lines and circular arcs is able to provide each aircraft in a group with a vortex-free trajectory for nearly simultaneous landing on a set of closely spaced parallel runways. Although the guidelines are described for aircraft on approach, the concepts presented are also applicable to departure, and to enroute operations.

Rossow, V. J.

"ORIGIN OF EXPONENTIAL SOLUTION FOR LAMINAR DECAY OF ISOLATED VORTEX"

Journal of Aircraft, Vol. 43, No. 3, May-June 2006, pp. 709-712

The origin of the exact, closed-form, self-similar exponential solution for the laminar decay of an isolated two-dimensional vortex in a viscous incompressible fluid is studied to find a proper name for the function. Two major contributions to the solution are the similarity parameter derived by Boltzmann and the derivation of the form of the solution by Carslaw for the diffusion of heat from a line source, that is, a spark or lightning stroke. Lamb adapted the heat transfer solution derived by Carslaw to the time-dependent diffusion of vorticity from a potential line vortex, and, after publication of his book, has provided a short, complete, and readily available derivation. Oseen's derivation followed about four years later and is not as complete. Various titles for the solution are believed to be appropriate, including a generic name such as exponential vortex solution, or the name of Lamb. The name of Lamb is probably the most appropriate because he was the first in existing literature to put the entire derivation together and because the presentation is compact, complete, and readily available.

Rossow, V. J.

"MEASURED CHANGES IN VORTEX WAKES WITH DOWNSTREAM DISTANCE"

AIAA Paper No. 1998-2425, Albuquerque, NM, June 1998

Data taken in the NASA 80- by 120-foot Wind Tunnel with 0.03 scale models of two subsonic transports is studied to determine what changes occur with downstream distance in the structure of lift-generated vortex wakes. Since the wind tunnel airstream has a turbulence level of about 0.5 percent, it is found that the downstream changes do not follow a uniform or steady decay process as predicted for vortices in non-turbulent flow fields. Instead of a monotonic decay, the vortices sometimes appear to intensify and sometimes decay much as might be expected in flight as the vortex centerlines become sinuous. Tests conducted on the measured vortex structures indicate that some of the profiles exhibit an exponential character like Lamb's and Squire's model for turbulent vortices. It was also found that most also indicate a logarithmic character suggested by Hoffman and Joubert. The measured rolling moments on following wings do not appear to decrease or increase consistently over the one-mile downstream distance in the wind tunnel.

Rossow, V. J.

"LIFT ENHANCEMENT BY AN EXTERNALLY TRAPPED VORTEX"

J. Aircraft, Vol. 15, No. 9, 1978, pp. 618-625

A theoretical study is made of the performance capabilities of a lift concept that utilizes a spanwise vortex over the upper surface of the wing. The vortex is generated by a vertical flap near the leading edge of the wing and maintained by suction through orifices in endplates at the wingtip. The analysis approximates the three-dimensional flowfield with a two-dimensional configuration that is mapped by conformal transformation into the flow about a circle. Theoretical solutions for a range of flap and orifice configurations predict that section lift coefficients up to around 10 can be achieved. It is concluded that such a lift concept is applicable to STOL aircraft if the vortex can be adequately stabilized and if the endplate suction can be generated efficiently.

Rossow, V. J.

"REDUCTION OF UNCERTAINTIES IN PREDICTION OF WAKE-VORTEX LOCATIONS"

AIAA Paper No. 2000-4130, August 2000, Denver, CO.

Lift-generated vortex wakes of subsonic transport aircraft are known to pose a rolling-moment hazard to in-trail following aircraft. Hazardous wake-encounters are now avoided by maintaining in-trail separation distances that are larger than needed for other operational considerations. To increase airport capacity, considerable effort has been devoted to the development of techniques and procedures by which vortex wakes can be accurately located as a function of time so that following aircraft can avoid them with less in-trail spacings. In order to improve the accuracy with which vortex wakes can be located, this paper reports on a study of the uncertainties associated with the determination of the time-dependent location of vortex wakes, and on ways to reduce the uncertainties. It is found that it is beneficial to reduce the uncertainties as much as possible by application of technology currently available for aircraft guidance, and for measurement of wind

velocity along the flight corridor by aircraft. It appears however, that the growth in the size of the hazardous region surrounding wake vortices is so rapid that it currently prevents the reduction to one minute of in-trail spacings between aircraft during approach to airports. Therefore, if airport capacity is to be increased, it is concluded that it will be necessary to also introduce some other system of sequential flight corridors like the ones illustrated here; e.g., to provide more lateral and vertical distance between the flight paths of aircraft so that wake encounters are avoided.

Rossow, V. J.

"AIRCRAFT SPACINGS THAT PRODUCE VORTEX-FREE REGION BELOW FLIGHT FORMATIONS"

AIAA Paper No. 2002-3263, St. Louis, MO, June 2002

A preliminary theoretical study is presented of a concept whereby the vortex wakes shed by a formation of aircraft can be redirected to produce a large region below the formation that is free of vortices. The redirection of the vortices is accomplished by first spacing the aircraft so that vortex pairs are formed between the wingtips of adjacent aircraft. If the aircraft spacings are within certain limits that are presented in the analysis described here, the self-induced velocity field of the vortex pairs causes all the inboard vortices to move upward rather than downward. One application for such a process is the deployment of paratroopers from aircraft so that, while descending to the ground, no parachute will come near the lift-generated vortices shed by the deploying, or other nearby aircraft. The purpose of the study is to find out whether spacings between aircraft in a formation can be established so that the lift-generated vortices being trailed move upward rather than downward. Since the vortices shed by a single aircraft must always descend, attention was focused on multiple aircraft formations. It was found that the method is aerodynamically feasible. That is, close formations of aircraft can be arranged so that all the inboard trailing vortices move upward rather than downward. The two outboard vortices then travel downward at a greatly reduced velocity that depends on the number of aircraft in the formation. All the inboard region below the formation is then free of vortices.

Rossow, V. J.

"USE OF INDIVIDUAL FLIGHT CORRIDORS TO AVOID VORTEX WAKES"

AIAA Paper No. 2002-4874, Monterey, CA, August 2002

Vortex wakes of aircraft pose a hazard to following aircraft until the energetic parts of their flow fields have decomposed to a harmless level. It is suggested here that in-trail spacings between aircraft can be significantly and safely reduced by designing an individual, vortex-free flight corridor for each aircraft. Since each aircraft will then have its own flight corridor, which is free of vortex wakes while in use by the assigned aircraft, the time intervals between aircraft operations can be safely reduced to the order of seconds. The productivity of airports can then be substantially increased. This paper explores how large the offset distances between operational corridors need to be to have them vortex free, and how airports need to be changed to accommodate an individual-flight-corridor process for landing and takeoff operations. Estimates are then made of the productivity of an individual-flight-corridor process

as a function of the in-trail time interval between operations for various values of wake decay time, runway width, and the velocity of a sidewind. The results confirm the need for short time intervals between aircraft operations if smaller offset distances and increased productivity are to be achieved.

Rossow, V. J.

"HISTORICAL OVERVIEW OF RESEARCH ON LIFT-GENERATED VORTEX WAKES"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002.

A historical overview is presented of early research conducted on the structure and modification of the vortices generated by the lifting surfaces of subsonic transport aircraft. After some general remarks on wake-vortex research, a summary is presented of the earliest published work on lift-generated wakes. A description is then given of the flight test program carried out by the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) of the United States during the late 1960's and early 1970's. The objective of the flight tests was to quantify the hazard posed by vortex wakes of aircraft, and to more clearly define the in-trail separation distances required between aircraft during landing and takeoff at airports. The flight test program led to a set of separation distances that insure safe approach and departure procedures at airports. Since across-wake procedures at cruise altitudes were not treated in detail, a study was undertaken to determine the structure of vortex wakes at altitude as a function of time. Photographs taken of condensation trails of aircraft, indicate that some instabilities cause the wake to grow rapidly in cross-section even before the long-wave instability begins to occur. It appears that a short-wave type of instability causes the vortex oval to grow by about a factor of 5, but does not lead to an incoherent wake structure.

Rossow, V. J.

"AIRCRAFT SPACINGS THAT PRODUCE VORTEX-FREE REGION BELOW FLIGHT FORMATIONS"

Journal of Aircraft, Vol. 38, No. 6, November-December 2001, pp. 977-987

A preliminary theoretical study is presented of a concept whereby the vortex wakes shed by a formation of aircraft can be redirected to produce a large region below the formation that is free of vortices. The redirection of the vortices is accomplished by first spacing the aircraft so that vortex pairs are formed between the wingtips of adjacent aircraft. If the aircraft spacings are within certain limits that are presented in the analysis, the self-induced velocity field of the vortex pairs causes all of the inboard vortices to move upward rather than downward. One application for such a process is the deployment of paratroopers from aircraft so that, while descending to the ground, no parachute will come near the lift-generated vortices shed by the deploying, or other nearby aircraft. The purpose of the study is to find out whether spacings between aircraft in a formation can be established so that the lift-generated vortices being trailed move upward rather than downward. Because the vortices shed by a single aircraft must always descend, attention was focused on multiple aircraft formations. It was found that the method is feasible and makes it possible to arrange close formations of aircraft so that all the inboard trailing vortices move upward rather than downward. The two outboard vortices then

travel downward at a greatly reduced velocity that depends on the number of aircraft in the formation. All the inboard region below the formation is then free of vortices. The stability of spacings between aircraft in successful formulations and the instrumentation required for implementation of the concept introduced are not treated.

Rossow, V. J.

"EXTENDED-BETZ METHODS FOR ROLL-UP OF VORTEX SHEETS"

J. Aircraft, Vol. 34, No. 5, September-October 1997, pp. 592-599.

The method derived for the roll-up of vortex sheets shed by lifting wings has been extended so that it can be applied to complex wakes that roll up into more than one vortex pair. Although these so-called extended-Betz methods often predict realistic vortex structures that approximate measured ones, the guidelines need to be improved if the predictions are to be reliable enough for such purposes as the assessment of the hazard posed by a wake or for the validation of other theoretical methods. This paper first describes the problem and then considers whether the five vortex invariants for the time-dependent motion of two-dimensional vortices can provide improved guidelines. In particular, the vortex invariants are studied to find out if they can be used to determine the initial division of the vortex sheet for separation into multiple vortices, and then possible merger into larger vortices. It is concluded that any refinements of the present forms of the extended-Betz methods to better define the structure of multiple vortex wakes will be very difficult and probably cannot be derived from the vortex invariants.

Rossow, V. J.

"ON USE OF GLOBAL POSITIONING TECHNOLOGY FOR SOLUTION OF WAKE-VORTEX PROBLEM"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 43-48

Improved precision of the flight paths used by aircraft to approach and depart airports becomes available when the Global Positioning System (GPS) is implemented at airports. An overview will be given of published information on how GPS precision guidance at airports can be used to avoid encounters with the lift-generated vortices shed by preceding aircraft during landing. It is pointed out that GPS provides two needed services to bring about improved avoidance capability. Firstly, GPS pseudolites are being built and installed at airports so that, when coupled with autopilot systems currently available on subsonic transport aircraft, the aircraft can make precision approaches for zero visibility landings. The same equipment can also be used for precision approaches for wake-vortex avoidance. Secondly, regular monitoring of atmospheric motions along the approach corridor can be obtained by use of GPS equipment on board aircraft that are in the flight corridors. That is, wind velocity is determined by use of GPS equipment to measure the ground speed of the aircraft and then combined with onboard instrumentation to measure the airspeed of the aircraft. The difference between the two measurements yields the wind velocity. When the measured wind velocities are

transmitted to an airport ground station, they are used to monitor whether air motions adverse for safety in the flight corridor are present. If any part of the corridor is unsafe, the spacing of the aircraft, or location of the flight corridor being used, is modified. It is estimated that the spacings between any combination of aircraft can then be safely reduced to a uniform 3 n. mi.

Rossow, V. J.

"WAKE VORTEX STRUCTURE FROM LIFT AND TORQUE INDUCED ON A FOLLOWING WING"

AIAA Paper No. 1993-3013, Orlando, FL, 1993

The large wind tunnels at NASA Ames Research Center are frequently used to obtain data on the potential rolling-moment hazard posed by the vortex wake of one aircraft on an aircraft that is following. The results have been found to be a reliable indication of the rolling moment to be expected during a full-scale flight encounter. A disadvantage of the technique is that the data taken in the wind tunnel applies only to the aircraft pair tested. An evaluation of the rolling moments for all possible encounter pairs then requires that all aircraft pairs or wings of interest be tested. Such a requirement is time consuming and expensive. For this reason, a procedure is being developed that uses vortex-lattice theory to interpret the lift and torque measured on a following model in a wind tunnel to retrieve the velocity distribution in the vortex wake that caused the induced forces. It will then be possible to use the wind tunnel data from one encounter pair to predict theoretically the rolling moments expected when any other aircraft or wing encounters the same vortex wake. A procedure used to retrieve the wake velocity distribution, and test cases used to check out and evaluate the procedure are first described. Since a procedure was found that provides very good results for theoretical cases, it is applied to wind tunnel measurements obtained with a model of a large wide-body transport aircraft as the wake-generating aircraft and with various following wings. The retrieved wake-vortex velocities are compared with each other and with measured upwash distributions. The comparisons made test not only the retrieval procedure presented here, but also test the ability of wake-vortex models to represent lift-generated wakes.

Rossow, V. J.

"VALIDATION OF VORTEX-LATTICE METHOD FOR LOADS ON WINGS IN LIFT-GENERATED WAKES"

J. Aircraft, Vol. 32, No. 6, November-December 1995, pp. 1254-1262

A study is described that evaluates the accuracy of vortex-lattice methods when they are used to compute the loads induced on aircraft as they encounter lift-generated wakes. The evaluation is accomplished using measurements made in the 80 by 120 ft Wind Tunnel of the lift, rolling moment, and downwash in the wake of three configurations of a model of a subsonic transport aircraft. The downwash measurements are used as input for a vortex-lattice code to compute the lift and rolling moment induced on wings that have a span of 0.186, 0.510, or 1.022 times the span of the wake-generating model. Comparison of the computed results with the measured lift and rolling-moment distributions using the vortex-lattice method is very reliable as long as the span of the encountering or

following wing is less than about 0.2 of the generator span. As the span of the following wing increases above 0.2, the vortex-lattice method continues to correctly predict the trends and nature of the induced loads, but it overpredicts the magnitude of the loads by increasing amounts.

Rossow, V. J.

"MEASUREMENTS IN VORTEX WAKES SHED BY CONVENTIONAL AND MODIFIED SUBSONIC AIRCRAFT"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 26-1 to 26-9

A theoretical and experimental program is underway at NASA Ames Research Center to first obtain a better understanding of the hazard posed by the vortex wakes of subsonic transports, and then to develop methods on how to modify the wake-generating aircraft to make the vortices less hazardous. This paper summarizes results obtained in the 80-by 120-Foot Wind Tunnel at NASA Ames Research Center on the characteristics of the vortex wakes that trail from 0.03 scale models of a B-747 and of a DC-10. Measurements are first described that were taken in the wakes with a hot-film anemometer probe, and with wings that range in size from 0.2 to 1.0 times the span of the wake-generating models, at downstream distances of 81 ft and 162 ft behind the wake-generating model; i.e., at scale distances of 0.5 and 1.0 mile. The data are then used to evaluate the accuracy of a vortex-lattice method for prediction of the loads induced on following wings by vortex wakes.

Rossow, V. J.

"WAKE-VORTEX SEPARATION DISTANCES WHEN FLIGHT-PATH CORRIDORS ARE CONSTRAINED"

J. Aircraft, Vol. 33, No. 3, May-June 1996, pp. 539-546

Improved precision of the flight paths used by aircraft to approach and depart airports will become available when the global positioning system (GPS) is implemented for air traffic control. It is suggested here that the improved precision be used to constrain the approach and departure corridors so that their cross-sectional sizes are small and constant in size. Such a constraint controls the flight paths of the aircraft, and consequently where their vortex wakes are placed, so that the likelihood of a wake-vortex encounter is reduced. If such a program is coupled with a wake-vortex advisory system, and with the operating system being planned for airports when GPS is implemented, preliminary indications are that the wake-vortex spacings currently being used for instrument flight conditions can be reduced to a uniform distance of 3 n mile. Furthermore, if the smaller GPS flight corridors are utilized by vortex advisory or forecast systems that are currently under development, the requirements to be placed on their capabilities can be substantially reduced.

Rossow, V. J.

"VORTEX STRUCTURES AND SPAN LOADINGS FROM ALLEVIATED WAKE MEASUREMENTS"

AIAA Paper No. 1997-2262, Atlanta, GA, June 1997

To find efficient wing designs that shed non-hazardous vortex wakes, an analysis is made of data taken in the wakes of three configurations of a subsonic transport. The study begins with the observation that alleviated-wake configurations often shed vortex wakes that induce about the same rolling-moment coefficient on following aircraft of all sizes. In order to determine the span loadings that correspond to these downstream vortex wakes, the analysis first finds the vortex structures that make up the measured downwash distributions. An inverse Betz method is then used to derive the corresponding span loadings. Analysis of these span loadings, and consideration of the induced drag and the energy in various wakes, yields information on some of the characteristics and penalties associated with the design of wings for less hazardous wakes. It is recommended that tools be developed for an optimization process that includes drag, wing-root bending moment, weight, complexity, etc. and the design of vertical and horizontal lifting surface for vortex wakes that have an acceptable hazard.

Rossow, V. J.

"ESTIMATE OF LOADS DURING WING-VORTEX INTERACTIONS BY MUNK'S TRANSVERSE-FLOW METHOD"

J. Aircraft, Vol. 27, No. 1, January 1990, pp. 66-74.

The inviscid, incompressible interaction of a wing with a vortex is studied by use of Munk's transverse-flow method. The method assumes that the loading on the wing is such that the local circulatory flow of the vortex is turned so that the wing and its vortex wake act as a barrier to the flow. This permits the analysis to be carried out by mapping the transverse flowfield into the flow about a circle to find the vorticity distribution in the wake. Closed-form expressions are then derived for the bound circulation in the wing and for the lift and rolling moment induced by the vortex on the encountering wing. Comparisons of the loads predicted by these relationships with those of vortex-lattice theory for a flat wing of a rectangular planform indicate that they accurately represent the various parameters when the aspect ratio of the encountering wing is less than about two. When flat rectangular wings of higher aspect ratios are considered, some sort of correction is needed. Examples are then presented to illustrate some applications of the results.

Rossow, V. J.

"PROSPECTS FOR ALLEVIATION OF HAZARD POSED BY LIFE-GENERATED WAKES"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 22-1 - 22-40

A review is first made of the successes and failures of previous attempts to bring about a substantial reduction in the rolling-moment hazard posed by the vortices that trail from the wings of subsonic transport aircraft. It is concluded that one of the more promising wake-alleviation schemes uses the span loading on the wing to produce vorticity distributions in the wake that will bring about large self-

induced cross-stream velocities. When this characteristic has been established, the vorticity in the wake is convected about so that the coherent rotary velocities are turned into large-scale random motions that decompose quickly into a non-hazardous wake. It appears that a wide range of span-loadings/wake-vortex distributions will produce these large-scale, self-induced motions. It remains however, to find those that bring about the desired wake dynamics with the least addition of drag and complexity to the wake-generating aircraft. A combined theoretical and experimental research program at NASA Ames Research Center is directed at finding design guidelines for implementation of wake-vortex alleviation on subsonic transport aircraft. The experimental part of the program will include tests in the 80- by 120-foot wind tunnel at scale distances up to one and one-half nautical miles.

Rossow, V. J.

"CONVECTIVE MERGING OF VORTEX CORES IN LIFT-GENERATED WAKES"

J. Aircraft, Vol. 14, No. 3, March 1977, pp. 283-290

The several wake vortices that originate from aircraft wingtips, flap edges, engine pylons, etc. usually merge, in the far field to form a single pair whose structure determines the hazard posed to encountering aircraft. To gain an understanding of the process whereby vortices merge and disperse, a numerical study was made of the interaction of two-dimensional, time-dependent, inviscid vortical regions. It was found that discrete boundaries, which depend on the structure and spacing of the vortices, distinguish merging from nonmerging situations. Furthermore, certain arrays of finite vortex cores that alternate in sign were found to undergo division and merging that may be useful in alleviating the hazard posed by aircraft wakes.

Rossow, V. J.

"ALLEVIATION OF LIFT-GENERATED WAKES BY VORTEX INTERACTIONS"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 150-160.

The requirements for wake alleviation by inviscid convective interaction of vortices are reviewed. It is concluded that these wake structures will disperse and merge to alleviate the wake hazard, but unacceptably large aerodynamic penalties occur when the required loadings are generated by use of trailing-edge flap deflections. It is suggested, therefore, that the vortex pairs of opposite sign be generated above or below the wing with devices such as fins, fences, engine thrust, etc. Guidelines for the effective disposition and strength of these extra or auxiliary vortices are derived and numerical examples are presented for various configurations. Results of some preliminary wind-tunnel experiments confirmed that vortex injection into a wake by fins provides alleviation and warrants further study to optimize the various design parameters.

Rossow, V. J.

"EFFECT OF WING FINS ON LIFT-GENERATED WAKES"

J. Aircraft, Vol. 15, No. 3, March 1978, pp. 160-167

A theoretical and experimental study has been made of the effect of wing-mounted fins on the vortex wakes of subsonic aircraft. The lateral lift on the fins injects vortices into the wake and redistributes the lift on the wing. The revised wake vorticity then interacts convectively to form a new configuration with low rotational velocities. Wind-tunnel tests were used to evaluate the alleviation achievable and to find the optimum values for the various fin parameters. It was found that vertical fins mounted on the upper surface of a wing could lower the wake-induced rolling moments on an encountering wing by a factor of 3 or more.

Rossow, V. J.

"EXPERIMENTAL INVESTIGATION OF WING FIN CONFIGURATIONS FOR ALLEVIATION OF VORTEX WAKES OF AIRCRAFT"

NASA TM-78520, November 1978, NASA Ames Research Center, Moffett Field, CA

A variety of fin configurations were tested on a model of the Boeing B747 in the 40- by 80-Foot Wind Tunnel at Ames Research Center and in the Ship Model Basin at Hydronautics, Inc., near Laurel, Maryland. The test results confirmed that a reduction in wake rolling moment is brought about by the vortex shed by the fins so that a wide range of designs can be used to achieve wake alleviation. It was also found that the reduction in wake-induced rolling moments is especially sensitive to the location of the smaller fins on the wing and that the penalties in lift and drag can probably be made negligible by proper fin design.

Rossow, V. J.

"WAKE HAZARD ALLEVIATION ASSOCIATED WITH ROLL OSCILLATIONS OF WAKE-GENERATING AIRCRAFT"

J. Aircraft, Vol. 23, No. 6, June 1986, pp. 484-491.

An explanation is provided for the difference in wake vortex alleviation achieved by roll oscillations during flight tests with B-747 and L-1011 transport aircraft. Both aircraft had their landing flaps extended and several spoilers deployed. Numerical analysis shows that the growth in amplitude of the initial waves in the vortex filaments is brought about by inviscid vortex interactions. In the case of the B-747, growth is enhanced by a vortex whose strength is about the same as the tip vortex that is shed near the fuselage by the inboard end of the flaps. Conversely, the L-1011 is estimated to shed a negligible fuselage vortex and to have a relatively strong wing tip vortex. These characteristics bring about a rotation and a large amplification of the initial waves in the vortex filaments in the wake of the B-747, but not in the L-1011 vortex wake. An aircraft following the B-747 would then experience only

intermittent encounters with the intense parts of the wake vortices, such that the time-averaged wake-induced rolling moment is substantially reduced.

Rossow, V. J.

"PROSPECTS FOR DESTRUCTIVE SELF-INDUCED INTERACTIONS IN A VORTEX PAIR"

J. Aircraft, Vol. 24, No. 7, July 1987, pp. 433-440

The vortex wakes of large transport aircraft can pose a hazard to smaller following aircraft in the vicinity of airports during landing and takeoff operations if certain separation guidelines are not observed. To reduce the hazard potential, and thereby the separation distances, efforts are being made to find more rapid wake-dissipation mechanisms. In this paper, numerical simulations are made of the three-dimensional time-dependent instabilities that might be initiated in a vortex pair by sinusoidal displacements of the filaments. The objective of the study is to find those displacements and phase angles that produce the most rapid destruction of the vortices. It is concluded that, of the wave patterns tried on the one pair of wake filaments, the only instability made that leads to destructive interactions of the vortices is the Scorer-Crow process.

Rossow, V. J.

"SPUR-TYPE INSTABILITY OBSERVED ON NUMERICALLY SIMULATED VORTEX FILAMENTS"

J. Aircraft, Vol. 25, No. 9, September 1988, pp. 835-841

An instability observed on vortex filaments during numerical simulations of the three-dimensional, time-dependent dynamics of vortex wakes is studied to determine when and why it occurs. It is concluded that the observed instability is a consequence of the use of straight-line vortex segments of finite length to model continuously curving vortex filaments. The instability appears to occur only when the link length is a sizeable fraction of the vortex span and, therefore, is not expected in an experiment. Guidelines are then given that help avoid numerical instabilities when vortex filaments are used in flow simulations.

Rossow, V. J.

"THEORETICAL STUDY OF LIFT-GENERATED VORTEX SHEETS DESIGNED TO AVOID ROLL-UP"

NASA TMX-62,304, September 1973, NASA Ames Research Center, Moffett Field, CA

The random motions of the vortex elements behind a wing that sheds a disturbed translating array of vortices are analyzed. The analysis indicates that the wake would diffuse and decay rapidly when viscosity is present and would produce small rolling moments on encountering aircraft. It was found that comparable results could also be achieved with an array consisting of vortices that are equal in magnitude but which alternate in sign. This observation indicates that random motion can probably be achieved with a variety of stepped loadings.

Rossow, V. J.

"ON THE INVISCID ROLLED-UP STRUCTURE OF LIFT-GENERATED VORTICES"

J. Aircraft, Vol. 10, No. 11, November 1973, pp. 647-650

A simple form is presented of the relationships derived by Betz for inviscid, fully developed structure of lift-generated vortices behind aircraft. An extension is then made to arbitrary span-load distributions by inferring guidelines for the selection of rollup centers for the vortex sheet. These techniques are easier to use and yield more realistic estimates of the rolled-up structure of vortices than the original form of Betz' theory when the span loading differs appreciably from elliptic loading.

Rossow, V. J.

"SURVEY OF COMPUTATIONAL METHODS FOR LIFT-GENERATED WAKES"

Aerodynamic Analyses Requiring Advanced Computers, Part I, NASA SP-347, 1975, pp. 897-923

The persistence and strength of vortices that trail behind heavy aircraft have recently caused attention to be focused on the potential hazard they present to smaller aircraft that might encounter them. A survey is made here of some computational methods that are used to predict the structure and duration of these lift-generated vortices and to explore mechanisms that might significantly reduce their lifetime and hazard potential.

Rossow, V. J.

"THEORETICAL STUDY OF LIFT-GENERATED VORTEX WAKES DESIGNED TO AVOID ROLLUP"

AIAA Journal, Vol. 13, No. 4, April 1975, pp. 476-484

Two hypothetical vortex wakes are introduced and studied theoretically to explore whether the rollup of lift-generated vortex sheets can be suppressed. The circulation distribution across each wake is specified such that one rotates and the other translates as a unit due to their self-induced velocities. Several span loadings are constructed from these solutions and the resulting inviscid wake structure is computed for several span lengths behind the generating wing by use of the discrete vortex method wherein the vortex wake is represented by an array of vortices. The final distribution of vortices is then used to estimate the rolling moment on an encountering wing. It is found that, even though the initial specified motions are not sustained, substantial reductions in rolling moment are predicted for certain ranges of the ratio of the span of the generating wing to the following wing.

Rossow, V. J.

"PREDICTION OF SPAN LOADING FROM MEASURED WAKE-VORTEX STRUCTURE -AN INVERSE BETZ METHOD"

J. Aircraft, Vol. 12, No. 7, July 1975, pp. 626-628

The Betz theory is based on the conservation equations for inviscid, two-dimensional vortices and predicts the circulation in the fully-developed vortex from the span loading on the generating wing. The relationship between span loading and vortex structure is extended here by introducing a so-called inverse rollup method that predicts the span loading on the generating wing when the radial distribution of circumferential velocity in the vortex is given. Several examples are presented wherein measured circumferential velocities in several vortices are used with the inverse method to infer the span loading that produced the vortices. These span loadings are compared with those predicted by vortex-lattice theory for the generating wing. The technique yields a fairly accurate representation of the span loading on the generating wing when turbulence effects are not large.

Rossow, V. J.

"INVISCID MODELING OF AIRCRAFT TRAILING VORTICES"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 9-60

A survey is presented of inviscid theoretical methods that have proven useful in the study of lift-generated vortices. Concepts derived using these inviscid theories are then presented which have helped to guide research directed at alleviating the velocities and rolling moments imposed on aircraft entering these wakes.

Rossow, V. J.

"LIFT-GENERATED VORTEX WAKES OF SUBSONIC TRANSPORT AIRCRAFT"

Progress in Aerospace Sciences, Vol. 35, No. 6, 1999, pp. 507-660

The flow fields of vortices, whether buoyancy-driven or lift-generated, are fascinating fluid-dynamic phenomena which often possess intense swirl velocities and complex time-dependent behavior. As part of the on-going study of vortex behavior, this paper presents a historical overview of research conducted on the structure and modification of the vortices generated by the lifting surfaces of subsonic transport aircraft. Although primarily presented from an experimental point of view, the derivation and use of relatively compact theoretical formulations and concepts are included. Experience with lift-generated wakes has shown that they are so complex that progress requires application of a combined theoretical and experimental research program, because either alone often leads to incorrect conclusions. The primary purpose of the research to be described is to find a way to reduce the hazard potential of lift-generated vortices shed by subsonic transport aircraft in the vicinity of airports during landing and takeoff operations. The information presented points out that the characteristics of lift-generated vortices are related to the aerodynamic shapes that produce them and that various arrangements of surfaces can be used to produce quite different vortex structures. It is

concluded that a satisfactory aerodynamic solution to the wake-vortex problem at airports has not yet been found, but a reduction in the impact of the wake-vortex hazard on airport capacity may soon become available through wake-vortex avoidance concepts currently under study.

Rossow, V. J.

"APPLICATION OF VORTEX INVARIANTS TO ROLL UP OF VORTEX PAIRS"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1098-1105.

A method developed by Betz for the rolled-up structure of vortices shed by isolated wing tips is extended to vortex pairs (two vortical regions of opposite sign), which are shed by wings of finite span. The present analysis again uses the invariants for the two-dimensional time-dependent motion of vortex systems, but the extension made here to vortex pairs depends primarily on the invariant for kinetic energy. It is found that the total energy in the flowfield can be separated into a part that governs the structure of each vortical region and a part that governs the spanwise distance between the centroids of the vortical regions. Consequently, the rules for the rolled-up structure of vortical regions are the same as the one derived by Betz. Because the analysis does not apply a constraint that forces the circular contours of constant circulation to coincide with streamline paths, the solution is labeled first order. A method that can be used to obtain second- and higher-order approximations is described. Application of the first-order method to the vortex wake of an elliptically loaded wing indicates that a first-order solution for vortex pairs is adequate for many engineering purposes. The method derived here for single vortex pairs also justifies the superposition of axially symmetric vortical cores to simulate complex vortex wakes.

Rossow, V. J.

"INITIATION OF LONG-WAVE INSTABILITY OF VORTEX PAIRS AT CRUISE ALTITUDES"

NASA/TM-2011-216420, Feb. 2011, NASA Ames Research Center, Moffett Field, CA.

Previous studies have usually attributed the initiation of the long-wave instability of a vortex pair to turbulence in the atmosphere or in the wake of the aircraft. The purpose here is to show by use of observations and photographs of condensation trails shed by aircraft at cruise altitudes that another initiating mechanism is not only possible but is usually the mechanism that initiates the long-wave instability at cruise altitudes. The alternate initiating mechanism comes about when engine thrust is robust enough to form an array of circumferential vortices around each jet-engine-exhaust stream. In those cases, initiation begins when the vortex sheet shed by the wing has rolled up into a vortex pair and descended to the vicinity of the inside bottom of the combined shear-layer vortex arrays. It is the in-and-out (up and down) velocity field between sequential circumferential vortices near the bottom of the array that then impresses disturbance waves on the lift-generated vortex pair that initiate the long-wave instability. A time adjustment to the Crow and Bate estimate for vortex linking is then derived for cases when thrust-based linking occurs.

Rossow, V. J. and Brown, A. P.

"EFFECT OF JET-EXHAUST STREAMS ON STRUCTURE OF VORTEX WAKES"

Journal of Aircraft, Vol. 47, No. 3, May-June 2010, pp. 1076-1083.

The study reported here was initiated by observations of condensation trails that occur behind transport aircraft at cruise altitudes under certain atmospheric conditions. The objective of the study reported is to explain why the structure of condensation trails behind aircraft at cruise altitudes differ in some respects from those predicted by classical theory for the roll-up of lift-generated vortex sheets. Because classical roll-up theory does not include the effect of jet-engine exhaust on wake structure, numerical simulations were carried out for the time-dependent interaction of jet-exhaust streams with lift-generated vortex distributions. The simulations indicate that inclusion of jet-exhaust effects produces results that more closely represent observed wakes than those calculated by means of classical roll-up theory. In particular, jet-exhaust streams appear to cause wakes to separate into several nearby parts so that the vertical depth of the wake is increased by over a factor of two. It is therefore recommended that wake-prediction methods include the effect of jet-exhaust streams during takeoff, climb and cruise. Current prediction methods for wake-hazardous regions during approach and landing at airports probably do not need to be changed because engine thrust is small during those operations.

Rossow, V. J. and James, K. D.

"OVERVIEW OF WAKE-VORTEX HAZARDS DURING CRUISE"

AIAA Paper 1999-3197, July 1999, Norfolk, VA.

A large amount of research effort has been devoted to the hazard posed by lift-generated wakes of subsonic transport aircraft during approach and departure at airports. In contrast, only a small amount of effort has gone into the corresponding potential hazard at cruise altitude. Since more frequent encounters with wakes may occur as the density of aircraft increases with time, improved knowledge is needed of the persistence and magnitude of the hazard posed by lift-generated wakes at cruise altitudes. This paper reviews and extends previous work by describing the various fluid dynamic stages that vortex wakes usually go through as they age. Estimates made of the potential hazard that each stage poses indicate that the rolling-moment hazard during an axial encounter of a vortex wake can be as severe at cruise as for approach at airports, but, as in the airport-approach case, the hazard only persists for several minutes (about 20 nmi) behind the generating aircraft. However, the hazard posed by the downwash in the wake persists for tens of minutes (about 200 nmi) behind the generating aircraft. The downwash hazard is realized as severe vertical loads. A technique for avoiding vortex wakes at cruise altitude is described.

Rossow, V. J. and James, K. D.

"OVERVIEW OF WAKE-VORTEX HAZARDS DURING CRUISE"

J. Aircraft, Vol. 37, No. 6, November-December 2000, pp. 960-975

A large amount of research effort has been devoted to the hazard posed by lift-generated wakes of subsonic transport aircraft during approach and departure at airports. In contrast, only a small amount of effort has gone into the corresponding potential hazard at cruise altitude. Since more frequent encounters with wakes may occur as the density of aircraft increases with time, improved knowledge is needed of the persistence and magnitude of the hazard posed by lift-generated wakes at cruise altitudes. This paper reviews and extends previous work by describing the various fluid dynamic stages that vortex wakes usually go through as they age. Estimates made of the potential hazard that each stage poses indicate that the rolling-moment hazard during an axial encounter of a vortex wake can be as severe at cruise as for approach at airports, but, as in the airport-approach case, the hazard only persists for several minutes (about 20 nmi) behind the generating aircraft. However, the hazard posed by the downwash in the wake persists for tens of minutes (about 200 nmi) behind the generating aircraft. The downwash hazard is realized as severe vertical loads. A technique for avoiding vortex wakes at cruise altitude is described.

Rossow, V. J. and Meyn, L. A.

"RELATIONSHIP BETWEEN VORTEX MEANDER AND AMBIENT TURBULENCE"

AIAA Paper No. 2006-7811, Wichita, KS, September 2006

Efforts are underway to increase the capacity of airports by use of closely-spaced parallel runways. If achieved safely and efficiently during both visual and instrument flight conditions, it will be necessary to develop more precise methods for the prediction of the motion and spread of the hazard posed by lift-generated vortex-wakes of aircraft. The purpose of the present study is to relate the magnitude of the meandering motion of vortex filaments to the turbulence level in the ambient flow field. The analysis begins with a study of the observations made in the airstreams of the two largest NASA wind tunnels where a small amount of data are available on the magnitude of turbulence-induced vertical and lateral meander of vortices shed by aircraft models. It is found that the turbulence level based on the maximum amplitude of meander is much less than the root-mean-squared value measured in the free-stream of the wind tunnel by use of hot-film anemometers. An analysis of the time-dependent motion of segments of vortex filaments as they interact with an eddy, indicates that the inertia of the filaments and of vortex ovals retards their motion enough in the early part of their travel to account for a large part of the difference in the two determinations of turbulence level. It is concluded that vortices do not move precisely with the fluid elements where they are embedded, but lag behind so that actual meander distances are a fraction of those estimated by the non-slip assumption. Application is then made of the foregoing relationships to meander distances used for the initiation of the long-wave instability, which contributes substantially to wake intrusion distances during landing and takeoff operations at airports. It was found that the best simulation predicts that ovals meander about 58% of the distance predicted without slippage. Because turbulent flow fields are a mixture of eddies rather than a single eddy, a further reduction to the 40% value found in the wind tunnels appears reasonable.

Rossow, V. J. and Meyn, L. A.

"GUIDELINES FOR AVOIDING VORTEX WAKES DURING USE OF CLOSELY SPACED PARALLEL RUNWAYS"

NASA/TM-2012-215985, January 2012, Ames Research Center, Moffett Field, CA.

A method is proposed for the estimation of the movement and spread of lift-generated vortex wakes as a function of time to better enable aircraft arriving at airports to avoid the hazards associated with the wakes of preceding aircraft. Operations on closely spaced parallel runways are used to illustrate how the method may be applied. The paper begins with an overview of the aerodynamic mechanisms that cause the hazardous parts of lift-generated wakes to spread and to move as a function of time. A computational method is then presented for the determination of the spread and movement of the hazardous parts of vortex wakes as a function of time during operations of aircraft as they approach closely spaced parallel runways for a landing. The results suggest guidelines for efficiently and effectively avoiding the vortex wakes of preceding aircraft. Because uncertainties occur in the theoretical tools developed and, in the measurements, made of the components of the time-averaged wind and its gust magnitudes, flight tests are recommended to confirm and refine the guidelines presented, and to verify the techniques used to measure the atmospheric parameters that control intrusion of the hazardous elements of lift-generated wakes into nearby parallel runways.

Rossow, V. J. and Meyn, L. A.

"GUIDELINES FOR AVOIDING VORTEX WAKES DURING USE OF CLOSELY-SPACED PARALLEL RUNWAYS"

AIAA Paper 2008-6907, Honolulu, HI, August 2008

This paper proposes a reliable method for estimation of the movement and spread of lift-generated vortex wakes as a function of time to better enable aircraft arriving at airports to avoid the hazards associated with the wakes of preceding aircraft. Operations on closely-spaced parallel runways illustrate how the method may be applied. An overview presents the aerodynamic mechanisms that cause the hazardous parts of lift-generated wakes to spread as a function of time. A computational method developed for determination of the spread of vortex wakes as a function of time is then applied to operations of aircraft as they approach closely-spaced parallel runways. The results suggest guidelines for efficiently and effectively avoiding the vortex wakes of preceding aircraft. Because the theoretical tools developed and the measurements of the components of the time-averaged wind and its gust magnitudes contain uncertainties, flight tests are recommended to confirm and to refine the guidelines presented, and to verify the techniques used to measure the atmospheric parameters that control wake intrusion.

Rossow, V. J. and Meyn, L. A.

"ON DATA SCATTER IN MEASURED LINKING TIMES FOR LIFT-GENERATED VORTEX PAIRS"

AIAA Paper No. 2008-338, Reno, NV, January 2008

The long-wave instability of a vortex pair spreads vortex wakes vertically and laterally faster than any other known aerodynamic mechanism. Initiated by turbulence in the atmosphere, the long-wave

instability occurs frequently. However, measurements in flight of the timing of the process for a range of atmospheric turbulence levels contain a large amount of scatter around predicted values. Possible causes for data scatter are studied by use of a formulation for initiation and growth of the instability that differs slightly from Crow's and Sarpakaya's. It is concluded that some of the scatter may be because the strength of vortex filaments in vortex pairs may sometimes be lower than the total centerline circulation on the wing, which causes the growth rate of the instability to be less than predicted. Another source for uncertainty may be caused by the way that the strength of the turbulence in the atmosphere was measured. Suggestions are made on how to use existing information to estimate the growth rate of the instability, and on how the turbulence in the atmosphere should be measured to achieve reliability.

Rossow, V. J. and Tinling, B. E.

"RESEARCH ON AIRCRAFT/VORTEX-WAKE INTERACTIONS TO DETERMINE ACCEPTABLE LEVEL OF WAKE INTENSITY"

J. Aircraft, Vol. 25, No. 6, June 1988, pp. 481-492.

An evaluation of the literature on large aircraft wake-vortex encounters in flight and in flight simulators has furnished an estimate of the level to which the vortex-induced rolling moments must be reduced to be perceived as nonhazardous at a 2-n.mi. separation distance. The criteria are based on the ratio of the vortex-induced acceleration in roll to the aileron-induced roll acceleration. A wake is acceptably alleviated if the ratio of vortex-to-aileron rolling moments is less than about 0.5. When a satisfactory alleviation scheme is identified, the alleviated vortex structure should be inserted into a simulator to ascertain whether the maximum bank angles induced are within tolerable limits.

Rossow, V. J., Corsiglia, V. R. and Phillippe, J. J.

"MEASUREMENTS OF THE VORTEX WAKES OF A SUBSONIC- AND A SUPERSONIC-TRANSPORT MODEL IN THE 40- BY 80-FOOT WIND TUNNEL"

NASA TM X-62,391, September 1974, NASA Ames Research Center, Moffett Field, CA.

The rolling moment induced on aircraft models in the wake of a model of a subsonic transport and of a supersonic transport was measured as a function of angle of attack for several configurations. A description of the tests and a presentation and analysis of the data is given.

Rossow, V. J., Corsiglia, V. R., Schwind, R. G., Frick, J. K. D. and Lemmer, O. J.

"VELOCITY AND ROLLING-MOMENT MEASUREMENTS IN THE WAKE OF A SWEPT-WING MODEL IN THE 40- BY 80-FOOT WIND TUNNEL"

NASA TM X-62414, April 1975, NASA AMES Research Center, Moffett Field, CA.

Measurements were made in the wake of a swept-wing model to study the structure of lift-generated vortex wakes shed by conventional span loadings and by several span loadings designed to reduce wake velocities. Variations in the span loading on the swept-wing generator were obtained by deflecting seven flap segments on each side by amounts determined by vortex-lattice theory to approximate the desired span loadings. The resulting wakes were probed with a three-component, hot-wire probe to measure velocity, and with a wing to measure the rolling moment that would be induced on a following aircraft. The experimental techniques are described, and the measured velocity and rolling moments are presented, along with some comparisons with the applicable theories.

Rossow, V. J., Fong, R. K., Wright, M. S. and Bisbee, L.

"VORTEX WAKES OF TWO TRANSPORTS MEASURED IN 80 BY 120 FOOT WIND TUNNEL"

J. Aircraft, Vol. 33, No. 2, March-April 1996, pp. 399-406

Measurements are reported on the characteristics of the vortex wakes that trail from 0.03-scale models of a B-747 and a DC-10. Included are the downwash distributions obtained with a hot-film anemometer probe for the standard landing configurations, and the rolling moments induced on various following wings by the vortex wakes of several configurations of both wake-generating models. Both sets of data are presented for downstream distances of 81 and 162 ft, i.e., scale distances of 0.5 and 1.0 mile.

Rossow, V. J., Hardy, G. H. and Meyn, L. A.

"MODELS OF WAKE-VORTEX SPREADING MECHANISMS AND THEIR ESTIMATED UNCERTAINTIES"

AIAA Paper No. 2005-7353, Arlington, VA, September 2005

One of the primary constraints on the capacity of the nation's air transportation system is the landing and takeoff capacities at its busiest airports. Efforts currently underway to increase the capacity of airports by use of closely-spaced runways are extended here by development of more precise methods for monitoring the motion and spread of the hazard posed by the lift-generated vortex wakes of aircraft, and their uncertainties. The study reported here reviews four aerodynamic mechanisms previously studied to estimate the uncertainties they carry with them for wake spreading and transport. In addition, two new models are introduced for the spreading mechanisms brought about by turbulence in the air where the vortices are embedded to enable more accurate estimates of the short-term spreading rate of vortex wakes that are of concern for nearly-simultaneous operations at airports. Suggestions are then made as to the theoretical and experimental research needed to increase the accuracy of and confidence level in the models presented. Best estimates and their uncertainties made with the improved wake models indicate that, if following aircraft are upwind of leading aircraft, the vortex wakes of the leading aircraft will not intrude into the airspace of the following aircraft for about 5s to 10s (based on pessimistic assumptions) for most atmospheric conditions. It was also found that longer time intervals before wake intrusion may be available when atmospheric turbulence levels are mild or moderate. However, if the estimates for increased along-trail

time intervals at these lower turbulence levels are to be reliable, further study is necessary to develop the necessary theory and instrumentation. When available it should be possible to accurately and reliably determine the time at which a given turbulence level will initiate and promote the long-wave instability of a vortex pair, and thereby when wake intrusion may occur.

Rossow, V. J., Sacco, J. N., Askins, P. A., Bisbee, L. S. and Smith, S. M.

"MEASUREMENTS IN 80- BY 120-FOOT WIND TUNNEL OF HAZARD POSED BY LIFT-GENERATED WAKE"

AIAA Paper No. 1993-3518-CP, Monterey, CA, August 1993.

The setup used and the results obtained during a wake vortex test conducted in the 80- by 120-Foot Wind Tunnel are described. The test is part of a research effort being carried out in support of a combined FAA and NASA program to study the characteristics of lift-generated vortices to safely increase airport capacity for subsonic transports. In support of that goal, the research is directed at supporting the effort to analyze current separation criteria at airports to find ways by which airport capacity can be increased. The material presented here is divided into three parts. In the first part, test results are obtained to confirm that data measured in the 80- by 120-Foot Wind Tunnel agree with those measured during the test program of the 1970's in the 40- by 80-Foot Wind Tunnel. In the second part, the potential hazard caused by the vortex wake of several configurations of a subsonic transport is evaluated by measuring the maximum rolling moment induced on following models. The wing spans of the followers vary from about 0.1 to 1.0 times the span of the wake-generating model. The configurations of the wake-generating model that are tested include the conventional landing and several modifications of it. In the third part, measured upwash distributions in the wake of three configurations of the wake generator are used with a vortex-lattice method to predict the lift and rolling moment on several following models. These results test the ability of the theory to predict induced loads on encountering aircraft.

Rossow, V. J., Sacco, J. N., Askins, P. A., Bisbee, L. S. and Smith, S. M.

"WIND TUNNEL MEASUREMENTS OF HAZARD POSED BY LIFT-GENERATED WAKES"

J. Aircraft, Vol. 32, No. 2, Mar.-Apr. 1995, pp. 278-284.

The results obtained during a wake-vortex test conducted in the NASA Ames Research Center 80- by 120-ft Wind Tunnel are described. The wind-tunnel test is part of an FAA and NASA program to study the characteristics of lift-generated vortices to safely increase airport capacity for subsonic transports. Data was first obtained to confirm that measurements in the 80- by 120-ft Wind Tunnel agree with those taken in the 40- by 80-ft Wind Tunnel during the test program of the 1970s. Measurements are then presented on the maximum rolling moment induced on following models of various sizes when they encounter the vortex wakes shed by several configurations of a subsonic transport. Finally, measurements are presented of the lift and rolling moment induced on various following models, and of the downwash, as a function of spanwise distance in the wake. The wing spans of the followers vary from 0.085 to 1.022 times the span of the wake-generating model.

Rotger, T.

"WAKE VORTICES"

International Wake Vortices Meeting, Transport Canada, Ottawa, Canada, December 1997.

Wake vortices constitute a severe hazard to following smaller aircraft. Therefore, separation rules must be observed. Airbus Industrie's concern as an aircraft manufacturer is both to reduce the impact of the leading aircraft's vortex and to improve flight safety for the following aircraft. These tasks need an enhanced understanding of wake vortex mechanisms (contribution from different parts of the aircraft to vortex formation, influence of flowfield and meteorological factors on vortex evolution and decay). A better control of wake vortex will allow air traffic management to apply less penalizing separations.

Roth, M.

"REVIEW OF ATMOSPHERIC TURBULENCE OVER CITIES"

Quarterly Journal of the Royal Meteorology Society, Vol. 126, 2000, pp. 941-990.

This paper provides a comprehensive, critical review of turbulence observations over cities. More than fifty studies are analyzed with their experimental conditions summarized in an appendix. The main results are based on 14 high-quality experiments which met criteria based on stringent experimental requirements. The observations are presented as non-dimensional statistics to facilitate comparison between urban studies and work conducted over other rough, inhomogeneous surfaces. Wake production associated with bluff bodies, and the inhomogeneous distribution of sources and sinks of scalars, result in a roughness sub-layer which for the studies reviewed extends to about 2.5 to 3 times the height of the buildings. It is shown that within this region the basis of several traditional micrometeorological approaches to describe the turbulent exchange is in doubt. There are strong similarities to flow over plant canopies, and many of the turbulence characteristics can be interpreted in the framework of a plane mixing layer. Future field observations should concentrate on the turbulent exchange near the top and within the urban canopy as well as within the urban boundary layer.

Rott, N.

"VORTEX DRIFT: A HISTORICAL SURVEY"

In: Symposium on Aerodynamics & Aeroacoustics, K. Y. Fung (editor), World Scientific Pub Co Inc, 1994, pp. 173-186.

A historical survey on the topic of the drift motion of a single isolated vortex is presented. Amongst works highlighted and summarized included those of Helmholtz, Kelvin, Kirchhoff, Grobli, Lamb, Hicks, Saffman, Fraenkel, Cantwell, Coles, Dimotakis, Rott, Tung, Ting, Stanaway, Spalart, and Maxworthy.

Rotta, N. R.

"THE STABILITY OF A VORTEX PAIR IN THE PRESENCE OF A GROUND PLANE"

Report 71-81A, June 1971, Oceanics Inc., Plainview, NY

The configuration stability of a vortex pair in the presence of a ground plane is examined. First the motion of a vortex in three dimensions is examined by the solution of matched asymptotic expansions in which the solution of the Navier-Stokes equations are constructed asymptotically. The explicit dependence of the stability on the perturbation wavelength is discussed and illustrated. Comparison of the present analysis in the limit of zero ground effect with photographs of vortices undergoing a configuration instability is made. The viscosity necessary for agreement is found to be on the order of the eddy viscosity for the turbulent line vortex, indicating the existence of turbulence in the vortex core.

Rotta, N. R. and Goodman, T. R.

"THE VORTEX WAKE HAZARD OF LARGE TRANSPORTS IN TAKEOFF AND LANDING"

Proceedings of the National Aerospace Electronics Conf., IEEE, 1971, pp. 4I-46

The configuration stability of a vortex pair in ground effect is examined for the trailing vortex wake of a large high weight aircraft. In ground effect, the large-scale motion of the vortices is adequately represented by the equations of potential theory which shows the vortex pair to descend to lower altitudes with increased separation. The stability theory indicates the vortex pair to be unstable, with the instability and time estimated for break-up shown to depend on the altitude at which the vortex pair was generated. The results of the study of the landing of a 747 shows good agreement with FAA full-scale flight tests for the behavior of the vortex wake at low altitudes.

Rotunno, R.

"THE FLUID DYNAMICS OF TORNADOES"

Annual Review of Fluid Mechanics, Vol. 45, 2013, pp. 59-84.

Because of the difficulty in making measurements under controlled conditions, most of what is known about the fluid dynamics of tornadoes comes from laboratory experiments that produce vortices with features like those observed in a tornado. Numerical simulation of laboratory experiments has become a valuable analytical tool owing to the greater ease of extracting data. The success of the numerical simulations has inspired better-defined numerical experiments capable of quantitatively describing the basic features of observed tornado vortices and has motivated simple fluid dynamical explanations. The present article reviews the state of knowledge concerning the fluid dynamics of tornadoes as found in laboratory and numerical analogs.

Rouwhorst, W. F. J. A., Groeneweg, J., Winckelmans, G. and Luckner, R.

"PILOTED SIMULATION RESULTS OF AN ONBOARD WAKE VORTEX DETECTION, WARNING AND AVOIDANCE SYSTEM AND COCKPIT DISPLAY ASPECTS"

ICAS 2008, Anchorage, AK, Sept. 200.

As part of the European project I-WAKE (Instrumentation systems for on-board WAKE vortex and other hazards detection, warning and avoidance), piloted flight simulations have been performed using an onboard wake vortex Detection, Warning and Avoidance (DWA) system concept including a novel cockpit Human Machine Interface (HMI). This HMI consisted of new information on a Primary Flight Display (PFD), the Navigation Display (ND) and a Vertical Navigation Display (VND). These concepts developed, associated wake alerting flight procedures, experimental set up and main results of the piloted study on a fixed base flight simulator will be addressed.

Roy, C. and Leweke, T.

"EXPERIMENTS ON VORTEX MEANDERING"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

The goal of this work is to provide detailed experimental data about vortex meandering. For this purpose, a single trailing vortex was generated in a water channel, using a NACA0012 half-wing. Nine configurations were tested, involving different free-stream velocities and angles of attack. The circulation-based Reynolds number varied in the range 8700-31500, and the axial velocity defect at the vortex center was between 27 and 55 percent of the maximum swirl velocity. Detailed measurements of the three-dimensional vortex velocity profiles were carried out at 11.2 chord lengths behind the wing, involving stereo-PIV and recentering of individual PIV fields before averaging. The first part of the meandering analysis deals with the statistics of the vortex center positions in the measurement plane. It is found that the amplitude of vortex displacement decreases with Reynolds number, in agreement with earlier findings by Devenport et al. (1996). The meandering amplitude is found to be of the order of the core radius, and the principal directions of motion are identified. In the second part, singular value decomposition (or Proper Orthogonal Decomposition - POD) analysis is carried out, using high-frequency vorticity data from PIV, as well as dye visualization images. After confirming that both inputs give similar results, long time series of dye visualizations are analyzed by POD. The most energetic perturbations are found to be displacement modes of the vortex. Spectral analysis of the projection of the time series on these displacement modes showed that they are characterized by low-frequency oscillations (at the fixed measurement position), corresponding to wavelengths in the frame of reference moving with the vortex that are two orders of magnitude larger than the vortex radius.

Roy, C., Leweke, T., Thompson, M. C. and Hourigan, K.

"EXPERIMENTS ON THE ELLIPTIC INSTABILITY IN VORTEX PAIRS WITH AXIAL CORE FLOW"

XXII International Congress of Theoretical and Applied Mechanics, Aug. 2008, Adelaide, Australia.

We show experimental results concerning the interaction of two parallel counter-rotating vortices presenting a jet-like axial velocity profile in their cores. The vortex pair is generated by two wings in a water channel; it is visualized by dye injection, and characterized quantitatively by stereoscopic Particle Image Velocimetry. Two types of three-dimensional instability are observed: the long-wavelength Crow instability and a short-wavelength core instability caused by the mutually induced elliptic deformation of the vortex streamlines. We here focus on the short-wave (elliptic) instability, for which we deduce the perturbation mode structure, which is different from the one observed without axial flow, the axial wavelength, and the growth rate from the experimental data. Comparisons are made with the results from a numerical linear stability analysis of the measured flow, and good overall agreement is found.

Roy, C., Leweke, T., Thompson, M. C. and Hourigan, K.

"EXPERIMENTS ON THE ELLIPTIC INSTABILITY IN VORTEX PAIRS WITH AXIAL CORE FLOW"

Journal of Fluid Mechanics, Vol. 677, 2011, pp. 383-416.

Results are presented from an experimental study on the dynamics of pairs of vortices, in which the axial velocity within each core differs from that of the surrounding fluid. Co- and counter-rotating vortex pairs at moderate Reynolds numbers were generated in a water channel from the tips of two rectangular wings. Measurement of the 3-dimensional velocity field was accomplished using stereoscopic particle image velocimetry, revealing significant axial velocity deficits in the cores. For counter-rotating pairs, the long-wavelength Crow instability involving symmetric wavy displacements of the vortices, could be clearly observed using dye visualization. Measurements of both the axial wavelength and the growth rate of the unstable perturbation field were found to be in good agreement with theoretical predictions based on the full experimentally measured velocity profile of the vortices, including the axial flow. The dye visualization further revealed the existence of a short-wavelength core instability. Proper orthogonal decomposition of the time series of images from high-speed video recordings allowed a precise characterization of the instability mode, which involves an interaction of waves with azimuthal wavenumbers $m=2$ and $m=0$. This combination of waves fulfills the resonance condition for the elliptic instability mechanism acting in strained vortical flows. A numerical 3-dimensional stability analysis of the experimental vortex pair revealed the same unstable mode, and a comparison of the wavelength and growth rate with the values obtained experimentally from dye visualizations shows good agreement. Pairs of co-rotating vortices evolve in the form of a double helix in the water channel. For flow configurations that do not lead to merging of the two vortices over the length of the test section, the same type of short-wave perturbations was observed. As for the counter-rotating case, quantitative measurements of the wavelength and growth rate, and comparison with previous theoretical predictions, again identify the instability as due to the elliptic mechanism, importantly, the spatial character of the short-wave instability for vortex pairs with axial flow is different from that previously found in pairs without axial flow, which exhibit an azimuthal variation with wavenumber $m=1$.

Roy, C., Schaeffer, N., Le Dizes, S. and Thompson, M.

"STABILITY OF A PAIR OF CO-ROTATING VORTICES WITH AXIAL FLOW"

Physics of Fluids, Vol. 20, No. 9, 2008, pp. 094101-094108

The three-dimensional linear temporal stability properties of a flow composed of two corotating q-vortices (also called Batchelor vortices) are predicted by numerical stability analysis. As for the corresponding counter-rotating case, when the axial flow parameter is increased, different instability modes are observed and identified as a combination of resonant Kelvin modes of azimuthal wavenumbers m and $m + 2$ within each vortex. In particular, we show that the sinuous mode, which is the dominant instability mode without axial flow, is stabilized in the presence of a moderate axial flow. Different types of mode with a large amplitude in the critical layer are also identified. For small separation distances (above the merging threshold), unstable eigenmodes, corresponding to axial wavenumbers that cannot be easily identified with simple resonant interactions of Kelvin modes, are also observed. Their growth rate is a substantial fraction of the growth rates of low-order resonant modes. The effects of the Reynolds number and vortex separation distance on the growth rate parameter map are considered. Finally, we analyze the similarities and differences between the stability characteristics of co- and counter-rotating vortex pairs.

Roy, C., Schaeffer, N., Le Dizes, S., Leweke, T., Thompson, M. C. and Hourigan, K.

"ELLIPTIC INSTABILITY IN VORTEX PAIRS WITH AXIAL CORE FLOW"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

The three-dimensional short-wavelength instability of a flow consisting of two parallel co- or counter-rotating vortices with a jet-like axial core flow is studied by both numerical stability analysis and experiments in a water channel. The numerical study focuses on the linear temporal stability properties of two co-rotating q-vortices (Batchelor vortices). As for the corresponding counter-rotating case, when the axial flow parameter is increased, different instability modes are observed and identified as a combination of resonant Kelvin modes of azimuthal wave numbers m and $m+2$ within each vortex, which characterizes the elliptic instability. We show that the sinuous mode, which is the dominant instability mode without axial flow, is stabilized in the presence of a moderate axial flow. Different types of modes with a large amplitude in the critical layer are also identified. In addition to the numerical analysis, experiments were carried out in a water channel, where vortex pairs with axial core flow were generated using two rectangular NACA 0012 half-wings. Detailed measurements of the three-dimensional velocity profiles characterizing the vortex base flow were made using stereoscopic Particle Image Velocimetry.

Ruan, H.

"INTERACTION OF A VORTEX PAIR AND A FREE-SURFACE: NUMERICAL SIMULATIONS"

PhD Thesis, May 2000, New Jersey Institute of Technology, Newark, NJ.

The interaction between a submerged vortex pair with a deformable free-surface in a viscous, incompressible fluid is directly simulated and the flow is thoroughly analyzed. This is a time-dependent nonlinear free-surface problem which we solve numerically by integrating the two-dimensional Navier-Stokes equations and using boundary-fitted coordinates capable of handling large free-surface deformations. In particular, the numerical simulation of the flow at relatively high Reynolds numbers (500, 1000, 2000) and relatively high Froude numbers (1.125, 2.0) is investigated and analyzed for the first time. Details are given regarding the space-time deformation of the free-surface, the path of the primary vortices, the formation of strong free-surface vorticity and kinetic energy, and the generation of turbulence in the flow. In particular, the turbulence characteristics have been explored at Reynolds number 1000. In this flow, we identified a thin free-surface layer characterized by very fast variations of the turbulent intensity, the kinetic energy dissipation and velocity fluctuations. The turbulence intensity reaches a maximum at the level of the center of the primary vortex, and then decreases significantly as the free-surface is approached. This decay is due to a very large increase of the turbulent kinetic energy dissipation at the free-surface and the formation of large vorticity peaks at the free-surface. Contrarily to previous findings, there is no redistribution of the turbulence intensity at the free-surface, that is a large increase of the horizontal velocity fluctuations at the expense of the vertical velocity fluctuation.

Ruan, X., Song, X. and Yamamoto, F.

"DIRECT MEASUREMENT OF THE VORTICITY FIELD IN DIGITAL PARTICLE IMAGES"

Experiments in Fluids, Vol. 30, 2001, pp. 696-704

A new method called direct measurement of vorticity (DMV) for digital particle images is described in this paper. Unlike previous methods for calculating the vorticity in particle image velocimetry (PIV), the vorticity is determined directly from the average angular displacement of rotation between two matched patterns. In order to improve the stability and precision of the angular displacement, polar coordinates are used instead of Cartesian coordinates to depict gray level patterns. The results of a Monte Carlo simulation of an Oseen-vortex flow indicate that the accuracy of the DMV method is independent of the spatial resolution of the velocity sampling, and the errors in the velocity field will not be propagated into the vorticity field as occurs with some finite difference methods. Therefore, the DMV method is a good method to be used to extract the vorticity field from velocity data that has higher levels of uncertainty.

Rubbert, P. E.

"AIRCRAFT WINGTIP VORTICITY REDISTRIBUTION APPARATUS"

US Patent 5,100,085, May 1992.

A rotor is mounted to an aircraft wing to recover induced drag associated with a wingtip vortex. When the rotor is placed in the vortex stream, the transverse component of relative wind encountered at selected increasing spanwise locations along the blade changes sign due to an increasing transverse

component of blade velocity and decreasing transverse component of vortex velocity with increasing distance from the axis of rotation. To maximize induced drag recovery, the blade is twisted in a spanwise direction so that the inner portion of the blade drives the blade, while the radially outward portion acts as a propeller to resist rotation. The induced drag recovery is in the form of thrust generated by the rotor blade.

Rubin, W. L.

"THE GENERATION AND DETECTION OF SOUND EMITTED BY AIRCRAFT WAKE VORTICES IN GROUND EFFECT"

J. of Atmospheric and Oceanic Technology, Vol. 22, May 2005, pp. 543-554

Sound recorded by the author in March 2002 at JFK International Airport shows that wake vortices in ground effect emit infrasound that is 1) more than 40 dB stronger than audible wake vortex sound; 2) substantially stronger than the infrasound component of wind noise and airport noise; and 3) comparable to, and often stronger than, the infrasound component of aircraft noise. Spectra and time plots of the magnitude of wake-vortex-generated sound are presented for aircraft landing on JFK runway 31R.

Rubin, W. L.

"RADAR-ACOUSTIC DETECTION OF AIRCRAFT WAKE VORTICES"

Journal of Atmospheric and Oceanic Technology, Vol. 17, August 2000, pp. 1058-1065

All aircraft produce trailing wake vortices as a direct consequence of generating lift. Vortices may be dangerous to following aircraft during takeoff and landing. An all-weather airport wake vortex sensor has been sought for more than 25 years as part of a ground-based wake vortex avoidance system that would enable current U.S. Federal Aviation Administration separation standards to be safely reduced under instrument and visual flight rule conditions. A sensitive all-weather radar-acoustic wake vortex sensor is described that satisfies wake vortex avoidance system requirements. Samples of recent vortex data gathered at New York's Kennedy International Airport are presented.

Rubin, W. L.

"GLIDE SLOPE SURVEILLANCE SENSOR"

US Patent 5,208,600, May 1993.

A surveillance sensor for detecting and monitoring aerodynamic conditions in a vicinity of an aircraft landing glide slope utilizes a radar transmitter to illuminate the glide slope. Radar reflections from aircraft induced vortices, clear air turbulence, and glide slope cross winds are received by a monopulse radar system wherein a sum beam doppler spectrum and a difference beam doppler spectrum for the radar returns is determined. The sum and difference beams doppler spectra are processed to

determine the aerodynamic conditions in the glide slope vicinity. These aerodynamic conditions are assessed to determine whether aerodynamic hazardous conditions exist in the glide slope region.

Rubin, W. L., Burnham, D. C., Spitzer, E. A. and Rudis, R. P.

"ROBUST LOW COST AIRPORT WAKE VORTEX SENSOR"

J. Aircraft, Vol. 37, No. 3, May-June 2000, pp. 377-382

A conventional Radar Acoustic Sounding System (RASS) atmospheric profiler has been converted into a wake vortex sensor that can detect/track/measure aircraft wake vortices under all weather conditions. The resulting wake vortex sensor has been operated automatically with real-time processing at New York's Kennedy International Airport, where wakes were detected from aircraft in all weight classes. Comparisons with other wake vortex sensors are presented and show consistent vortex tracking with a very low false alarm rate. Possible applications of the sensor to wake vortex avoidance systems are discussed.

Rudis, R. P. and Burnham, D. C.

"ANEMOMETER ARRAY AND METEOROLOGICAL DATA: May 1998 SOCRATES TEST"

DOT-VNTSC-FAA-98-13, June 1999, DOT Volpe National Transportation Systems Center, Cambridge, MA.

In support of the Federal Aviation Administration, the Volpe National Transportation Systems Center (Volpe Center) is conducting an evaluation of a laser-based system concept called SOCRATES to determine its possible application in detecting potentially hazardous meteorological and wake turbulence phenomena. SOCRATES technology uses a laser beam to detect sound in the atmosphere. The objectives of the test were to define the nature of wake vortex acoustic signals and evaluate the capability of the SOCRATES technology to detect those acoustic signals. The SOCRATES test was conducted at the Wake Vortex Test Site at Kennedy Airport from May 13, 1998 through May 22, 1998. This report presents the data obtained by the Volpe Center using the ground-wind line to provide wake vortex lateral position ground truth and the data obtained using supplementary instrumentation.

Rudis, R. P. and Burnham, D. C.

"ANEMOMETER ARRAY AND METEOROLOGICAL DATA: MAY 1998 SOCRATES TEST"

DOT/FAA/RD-98, January 1999, DOT Volpe National Transportation Systems Center, Cambridge, MA

SOCRATES sensor technology uses laser beams to simulate an array of microphones. One possible application of this technology is to detect and track aircraft wake vortices by means of the sound emitted. In May 1998, a feasibility test was conducted at the approach to Runway 31R at JFK International Airport. Vortex lateral position was measured using a 700-foot array of horizontal and vertical single-axis anemometers mounted on 28-foot poles. Meteorological sensors provided information about the state of the atmosphere. This report (with an accompanying CD-ROM) presents

the aircraft arrival, wake vortex, and meteorological data from this test, including descriptions of processing algorithms and database formats.

Rudis, R. P. and Burnham, D. C.

"CROSSWIND MEASUREMENT AND FORECASTING REQUIREMENTS FOR AIRCRAFT WAKE VORTEX AVOIDANCE SYSTEM"

Poster Paper 3.1, AMS 7th Conf. on Aviation, Range and Aerospace Meteorology, Feb. 1997, Long Beach, CA.

Systems have been designed to permit reduced wake-vortex separations, and hence increased airport capacity, under appropriate crosswind conditions. Different systems were designed for landing operations on a single runway and on close-spaced parallel runways (less than 2500 feet apart).

Rudis, R. P., Burnham, D. C. and Jacobs, L.

"AVOSS WINDLINE AT DALLAS/FT. WORTH AIRPORT, VOLUME 1: INSTALLATION AND OPERATION"

DOT-VNTSC-RSPA-01-01, May 2001, DOT Volpe National Transportation Systems Center, Cambridge, M.

A 259-meter windline, with horizontal and vertical single-axis anemometers mounted on 9-meter poles, was installed at the Dallas/Ft. Worth Airport under the approach to Runway 17C, as part of NASA's Aircraft VOrtex Spacing System (AVOSS) development program. Real-time processing algorithms provided wake vortex tracking information. Additional weather sensors, including additional anemometers, temperature and dewpoint, weather sensor and a sodar wind profiler were deployed at various times of windline operation. Wake and meteorological data were provided in real time to AVOSS. This report, Volume 1 of a two-volume report, describes the installation, the data processing algorithms, and the data files supplied to AVOSS.

Rudis, R. P., Burnham, D. C. and Jacobs, L.

"AVOSS WINDLINE AT DALLAS/FT. WORTH AIRPORT, VOLUME 2: DATA BASE OF GROUND-BASED ANEMOMETER MEASUREMENTS OF WAKE VORTICES"

DOT-VNTSC-RSPA-01-02, May 2001, DOT Volpe National Transportation Systems Center, Cambridge, M.

A 259-meter array of horizontal and vertical single-axis anemometers mounted on 9-meter poles was installed at the Dallas/Ft. Worth Airport (DFW) under the approach to Runway 17C, as part of NASA's Aircraft VOrtex Spacing System (AVOSS) development program. Real-time processing algorithms were developed that based the vortex detection threshold on the turbulence level. Data from more than 70,000 landings have been recorded and processed. This report documents the current state of algorithm development and provides processed data for other researchers to analyze.

Rudis, R. P., Burnham, D. C. and Janota, P.

"WAKE VORTEX DECAY NEAR THE GROUND UNDER CONDITIONS OF STRONG STRATIFICATION AND WIND SHEAR"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 11-1 to 11-10

Using the tower fly-by method, decay measurements were made on wake vortices generated by B-727, B-757 and B-767 aircraft. In addition to a 60-meter instrumented tower, two remote sensing systems were deployed: (1) Laser Doppler Velocimeter (LDV) (high resolution vortex profiles at ranges of 40-200 meters) and (2) Monostatic Acoustic Vortex Sensing System (MAVSS) (lower resolution profiles up to 500 meters beyond the tower location). Typical early morning meteorology during the test period consisted of stratified drainage flows. Because of the persistent crosswind, the MAVSS gave the most complete vortex decay information. Meteorological conditions were measured by instruments on the tower and on a tether sonde. The analysis looked for statistical relationships between vortex lifetime and several meteorological parameters, treated independently. Due to the meteorological conditions of stratification, low turbulence and wind shear, the upwind vortex lasted longer than the downwind vortex; the circulation remained above 140 m²/s for up to 125, 150 and 170 seconds for the B-727, B-757 and B-767, respectively. However, in every case, the crosswind was strong enough to sweep both wake vortices away from the generating location; in some cases, the vortices traveled more than 500 meters laterally. Although these durations are much longer than the normally observed vortex lifetimes, they are related, according to the analysis, to strong crosswind shear coupled with low turbulence levels. While this long vortex migration at the observed strength levels might represent a potential vortex encounter hazard for operations on a downwind parallel runway, the drainage flow conditions which led to this unusual vortex behavior would be unlikely to occur at most airports.

Rudis, R. P., Wang, F. Y. and Daskalakis, A. C.

"STATUS REPORT SOCRATES CONCEPT EXPLORATION EFFORT"

DOT-VNTSC-RSPA-01-04, October 2001, Volpe National Transportation Systems Center, Cambridge, MA

Project SOCRATES, development of a technology to detect hypothesized acoustic emanations from wake vortices, has been underway for more than four years. This report discusses several aspects of this project including the current level of knowledge concerning wake vortex acoustic properties, SOCRATES detection technology, and wake turbulence sensor deployment issues. Three recommendations are offered to restructure the programmatic approach of Project SOCRATES to reduce the high risk and high cost should the government decide to continue to pursue this program.

Rudland, R. S.

"USE OF SIMULATION IN EVALUATING AN EARLY WARNING SYSTEM FOR AVOIDANCE OF JUMBO JET TRAILING VORTEX TURBULENCE IN AIRPORTS"

Proceedings of Eighth Annual Pittsburgh Conf., Volume 8 - Modeling and Simulation, Inst. Soc. of America, Pittsburgh, PA, April 1977, pp. 393-396

Wake turbulence from large aircraft has created a safety hazard for smaller aircraft that land soon after a Jumbo-Jet. A laser detection system was developed to monitor wake turbulence in the airport and to provide early warning to the air traffic controller. Since each part of the system has been developed separately, proper integration of this system depends on simulation of realistic landing patterns with wake turbulence to see if the detection system and the warning system can provide the controller with the right information at the right time. A description of the simulation model is developed to be able to provide random landing patterns to create realistic aircraft sequencing. With this simulation model controller performance can be evaluated.

Rudland, R. S.

"AVOIDANCE OF TRAILING VORTEX HAZARD BY AIRPORT WARNING SYSTEM."

The 1972 NASA-ASEE Summer Faculty Fellowship Program Research Reports, NASA and American Society of Engineering Education, September 1972, pp. 507-532. (Also, NASA CR-61396..

To improve airport traffic operation near jumbo jets, an airport trailing vortex warning system (ATVWS) was developed to predict trailing vortex turbulence. The ATVWS consists of a computer simulator which is compatible with a vortex sensor such as a laser Doppler velocimeter or an acoustic radar. A study of the traffic in one of the ten busiest airports, Atlanta Municipal Airport, provided information on traffic patterns of a statistical nature. With this information, airport traffic patterns can be studied and hazard statistics developed. Based on a careful study of this simulation model, requirements for the development and testing of an ATVWS can be accurately specified.

Rudolph, J. F.

"AIRCRAFT WAKE TURBULENCE"

Economics of Air Safety and Long-Range Safety Research and Development, Proceedings of the 26-th Annual International Air Safety Seminar, Flight Safety Foundation, November 1973, pp. 31-47

Discussion of an FAA R&D program aimed at coping with current wake vortex problems which are significant in large transport aircraft. The program is planned to increase aircraft safety in terms of vortex hazard and allow a large increase in airport capacities by reducing the takeoff and landing spacing. The major points of the program include aircraft design modifications for wake vortex elimination, vortex dissipation methods, and automatic wake vortex avoidance systems.

Ruggi, E. and Hanna, M.

"AIR VELOCITY DISTRIBUTION BEHIND WING-MOUNTED AIRCRAFT ENGINES"

Transport Canada TR 13480E, October 1999, APS Aviation Inc, Montreal, Quebec, Canada.

This study had focused on two main objectives: Acquisition of experimental data on the air velocity distribution experienced in the blast from wing-mounted aircraft engines at idle during deicing operations, and Development and evaluation of a method that could be used as a safety check for deicing truck stability, and incorporated into an SAE standard. Two supplemental objectives were also addressed: Measurement of air velocities in the vicinity of the Boeing 777 auxiliary power unit (APU) exhaust, and Measurement of the air velocity profiles 100 m behind a Boeing 777 engine at three-quarter throttle. Nineteen tests were conducted on nine different aircraft at three airports. Air velocity measurements were recorded on all occasions and were considered as a function of aircraft geometry and engine rating. Peak air velocity measurements were recorded for the various aircraft. The Airbus A320 recorded the highest air velocity, 180 km/h. The overturning moment on a deicing truck subject to the jet blast of a wing-mounted aircraft engine at idle was found to be 7.4 percent of that required to overturn the truck. A viable and repeatable preliminary test method was developed. Boeing 777 APU tests observed excessively high heat and recorded an air velocity more than 200 km/h. Boeing 777 three-quarter throttle tests recorded an air velocity more than 190 km/h, but were discontinued because of equipment damage. The stability of the deicing truck during this test was affected by the overwhelming wave of air created by the aircraft engine and the truck was considered unsafe.

Ruith, M. R., Chen, P. and Meiburg, E.

"DEVELOPMENT OF BOUNDARY CONDITIONS FOR DIRECT NUMERICAL SIMULATIONS OF THREE-DIMENSIONAL VORTEX BREAKDOWN PHENOMENA IN SEMI-INFINITE DOMAINS"

Computers & Fluids, Vol. 33, 2004, pp.1225-1250

The suitability of various open boundary conditions is evaluated for direct numerical simulations of three-dimensional, incompressible, spatially and temporally evolving, swirling laminar jets in domains that extend to infinity in the downstream and radial direction. From the point of view of specifying conditions at the open boundaries, this class of flows is particularly challenging due to its ability to support traveling waves. Towards this end, several radial boundary conditions are implemented and tested with respect to their ability to conserve local and global mass, to handle low and high entrainment flow, and to avoid the introduction of artificial waves propagating from the boundaries into the interior: a free-slip condition, two types of homogeneous Neumann conditions, and a radiation condition in spirit of the outflow boundary condition. Global mass is conserved automatically within machine accuracy in the free-slip and simple radiation case, while the Neumann conditions require some iterative modification to conserve mass. This yields a computationally less efficient scheme which additionally exhibits poorer conservation properties due to the limited number of iterations. The free-slip condition typically requires the largest radial extent of the computational domain due to its impermeable character which is particularly problematic for the high entrainment flow. Hence, the radiation condition has been found as the most suitable lateral boundary condition for both high and low entrainment jets.

Ruith, M. R., Chen, P., Meiburg, E. and Maxworthy, T.

"THREE-DIMENSIONAL VORTEX BREAKDOWN IN SWIRLING JETS AND WAKES: DIRECT NUMERICAL SIMULATION"

J. Fluid Mech., Vol. 486, 2003, pp. 331-378

Vortex breakdown of nominally axisymmetric, swirling incompressible flows with jet- and wake-like axial velocity distributions issuing into a semi-infinite domain is studied by means of direct numerical simulations. By selecting a two-parametric velocity profile for which the steady axisymmetric breakdown is well-studied (Grabowski & Berger 1976), issues are addressed regarding the role of three-dimensionality and unsteadiness with respect to the existence, mode selection, and internal structure of vortex breakdown, in terms of the two governing parameters and the Reynolds number. Low Reynolds numbers are found to yield flow fields lacking breakdown bubbles or helical breakdown modes even for high swirl. In contrast, highly swirling flows at large Reynolds numbers exhibit bubble, helical or double-helical breakdown modes, where the axisymmetric mode is promoted by a jet-like axial velocity profile, while a wake-like profile renders the flow helically unstable and ultimately yields non-axisymmetric breakdown modes. It is shown that a transition from super- to subcritical flow, as defined by Benjamin (1962), accurately predicts the parameter combination yielding breakdown, if applied locally to flows with supercritical inflow profiles. Thus, the basic form of breakdown is axisymmetric, and a transition to helical breakdown modes is shown to be caused by a sufficiently large pocket of absolute instability in the wake of the bubble, giving rise to a self-excited global mode. Two distinct eigenfunctions corresponding to azimuthal wavenumbers $m = -1$ and $m = -2$ have been found to yield a helical or double-helical breakdown mode, respectively. Here the minus sign represents the fact that the winding sense of the spiral is opposite to that of the flow.

Rule, J. A. and Bliss, D B.

"PREDICTION OF TURBULENT TRAILING VORTEX STRUCTURE FROM BASIC LOADING PARAMETERS"

AIAA Paper No. 1996-2495, June 1996, New Orleans, LA.

A novel analytical method has been developed to accurately predict the core structure of a fully developed trailing vortex. Properties in the trailing vortex are calculated from the load distribution on the generating wing, and satisfy a set of fundamental conservation laws. The present rollup model is based on the Betz method, with significant improvements which address both viscous effects in the vortex core region, and also the effects of viscous drag on the generating wing. Turbulent mixing in the core is handled implicitly through the appropriate choice of solution velocity profiles, which contain free constants. These constants are determined uniquely by conserving properties between an inviscid Betz-type vortex and a vortex with experimentally consistent velocity distribution. The method is developed for arbitrary wing loading and results are presented for several important cases. Comparison with experiment demonstrates the accuracy of the model.

Rule, J. A. and Bliss, D. B.

"PREDICTION OF VISCOUS TRAILING VORTEX STRUCTURE FROM BASIC LOADING PARAMETERS"

AIAA Journal, Vol. 36, No. 2, February 1998, pp. 208-218

An analytical method has been developed to predict the structure of a fully developed trailing vortex with a viscous core. Vortex structure is calculated from the load distribution on the generating wing and fundamental conservation laws are satisfied. The present rollup model implicitly addresses viscous effects in the vortex core region by assuming a turbulent mixing process in the core during formation. Mixing theory suggests the appropriate functional form of the solution velocity profiles within this region, with constants that are determined uniquely by the method for arbitrary wing loading distributions. Important structural properties such as vortex strength, core size, and peak swirl velocity are calculated directly from these solution constants. The viscous core model was validated against two recent experimental studies, which provided new insight into vortex growth.

Rumsey, C. L. and Lee-Rausch, E. M.

"NASA TRAPEZOIDAL WING COMPUTATIONS INCLUDING TRANSITION AND ADVANCED TURBULENCE MODELING"

Journal of Aircraft, Vol. 52, No. 2, March-April 2015, pp. 496-509.

Flow about the NASA trapezoidal wing is computed with several turbulence models by using grids from the first high-lift prediction workshop to advance understanding of computational fluid dynamics modeling for this type of flowfield. Transition is accounted for in many of the computations. In particular, a recently developed four-equation transition model is used and works well overall. Accounting for transition tends to increase lift and decrease moment, which improves agreement with the experiment. Upper surface flap separation is reduced, and agreement with experimental surface pressure and velocity profiles is improved. The predicted shape of wakes from upstream elements is strongly influenced by grid resolution in regions above the main and flap elements. Turbulence model enhancements to account for rotation and curvature have the general effect of increasing lift and improving the resolution of the wing-tip vortex as it convects downstream. However, none of the models improve the prediction of flap surface pressures near the wing tip.

Rumsey, Jr., C. B.

"A WATER TUNNEL INVESTIGATION OF A SMALL SCALE ROTOR OPERATING IN THE VORTEX RING STATE"

MS Thesis, June 2003, Naval Postgraduate School, Monterey, CA.

Motivation to expand the understanding of a helicopter rotor descending into the vortex ring state (VRS) stems from the aircraft mishaps that have plagued the helicopter community. The V-22 has become the most recent victim of encounters with VRS. The onset of VRS is associated with the collapse of the helical vortex wake in the plane of the rotor. The resulting wake disturbances develop an irregular and aperiodic flow. Rotor blade interaction with the disturbed vortices causes large variations in the blade spanwise aerodynamic load distribution. Harmonic analysis of the loading indicates that higher harmonic content becomes prevalent in this state. The dynamic flow similarities achieved in a water tunnel are used to explore flow visualization and conduct vibration analysis of a rotor system

operating in the VRS. A scaled rotor system was operated in the NPS Aeronautical Engineering Department's water tunnel. Sensors were used to gather thrust and vibration power spectrum data when operating in VRS. Experimental results correlate with full scale flight data and show a significant increase in the vibration levels of the even multiples of the blade passage frequency. The relative strength of these higher harmonics can be used as an indicator of impending VRS encounters.

Rusak, Z.

"AXISYMMETRIC SWIRLING FLOW AROUND A VORTEX BREAKDOWN POINT"

Journal of Fluid Mechanics, Vol. 323, 1996, pp. 79-105.

The structure of an axisymmetric and inviscid swirling flow around a vortex breakdown point is analyzed. The model assumes that a free axisymmetric bubble surface is developed in the flow with a stagnation point at its nose. The classical Squire-Long equation for the stream function $\psi(x,y)$ (where $y = (r^2)/2$) is transformed into a free boundary problem for the solution of $y(x,\psi)$. The development of the flow is studied in three regions: the approaching flow ahead of the bubble, around the bubble nose and around the separated bubble surface. Asymptotic expansions are constructed to describe the flow ahead of and behind the stagnation point in terms of the radial distance from the vortex axis and from the bubble surface, respectively. In the intermediate region around the stagnation point, the flow is approximated by an asymptotic series of similarity terms that match the expansions in the other regions. The analysis results in two possible matching processes. Analytical expressions are given for the leading term of the intermediate expansion for each of these processes. The first solution describes a swirling flow around a constant-pressure bubble surface, over which the flow is stagnant. The second solution represents a swirling flow around a pressure-varying bubble surface, where the flow expands along the bubble nose. In both solutions, the bubble nose has a parabolic shape, and both exist only when $H' > 0$ (where H' is the derivative at the vortex center of the total head H with the stream function ψ , and can be determined from the inlet conditions). This result is shown to be equivalent to Brown & Lopez's (1990) criterion for vortex breakdown. Good agreement is found in the region around the stagnation point between the pressure-varying bubble solution and available experimental data for axisymmetric vortex breakdown.

Rusak, Z. and Lee, J. H.

"THE CRITICAL SWIRL OF COMPRESSIBLE VORTEX FLOWS"

AIAA Paper No. 2002-0159, Reno, NV, January 2002.

The effect of compressibility on the critical swirl level for breakdown of subsonic vortex flows in a straight circular pipe of finite length is studied. This work extends the critical-state concept of Benjamin to include the influence of Mach number on the flow behavior. The analysis is based on a linearized version of the equations for the motion of a steady, axisymmetric, inviscid, and compressible swirling flow of a perfect gas. The relationship between the velocity, density, temperature, and pressure perturbations to a base columnar flow state are derived. An eigenvalue problem is formulated to

determine the first critical level of swirl at which a special mode of a non-columnar small disturbance may appear on the base flow. It is found that when the characteristic Mach number of the base flow tends to zero the eigenvalue problem and the critical swirl are the same as defined by Wang and Rusak in their study of incompressible swirling flows in pipes. As the characteristic Mach number is increased, the critical swirl level increases and the flow perturbation expands in the radial direction. As the Mach number is increased toward a certain limit value related to the core size of the vortex, the critical swirl reaches very large values and becomes singular. The present results indicate that the axisymmetric breakdown of high Reynolds number compressible vortex flows may be delayed with the increase of the flow Mach number.

Rusak, Z. and Lee, J. H.

"ON THE STABILITY OF A COMPRESSIBLE AXISYMMETRIC ROTATING FLOW IN A PIPE"

J. Fluid Mech., Vol. 501, 2004, pp. 25-42

The linear stability of a compressible inviscid axisymmetric and rotating columnar flow of a perfect gas in a finite-length straight circular pipe is investigated. This work extends a previous analysis to include the influence of Mach number on the flow dynamics. A well-posed model of the unsteady motion of a swirling flow, with inlet and outlet conditions that may reflect the physical situation, is formulated. The linearized equations of motion for the evolution of infinitesimal axially symmetric disturbances are derived. A general mode of disturbance, that is not limited to the axial-Fourier mode, is introduced and an eigenvalue problem is developed. It is found that a neutral mode of disturbance exists at 'the critical swirl ratio for a compressible vortex flow'. The flow changes its stability characteristics as the swirl ratio increases across this critical level. When the swirl ratio is below the critical level (supercritical flow), an asymptotically stable mode is found and, when it is above the critical level (subcritical flow), an unstable mode of disturbance develops. This result cannot be predicted by any of the previous stability criteria. When the characteristic Mach number of the base flow tends to zero, the results are the same as found for incompressible swirling flows in pipes. The growth rate ratio is positive for all Mach numbers, but decreases as Mach number is increased. This ratio vanishes at the limit Mach numbers, but decreases as Mach number is increased. This ratio vanishes at the limit Mach number at which the critical swirl tends to infinity. The present results also demonstrate that the axisymmetric breakdown of high-Reynolds-number compressible vortex flows may be delayed to higher swirl ratios with the increase of the incoming flow Mach number.

Rusak, Z. and Lee, J. H.

"THE EFFECT OF COMPRESSIBILITY ON THE CRITICAL SWIRL OF VORTEX FLOWS IN A PIPE"

J. Fluid Mech., Vol. 461, 2002, pp. 301-319

The effect of compressibility on the critical swirl level for breakdown of subsonic vortex flows in a straight circular pipe of finite length is studied. This work extends the critical-state concept of Benjamin (1962) to include the influence of Mach number on the flow behavior. The analysis is based on a

linearized version of the equations for the motion of a steady, axisymmetric, inviscid, and compressible swirling flow of a perfect gas. The relationship between the velocity, density, temperature, and pressure perturbations to a base columnar flow state are derived. An eigenvalue problem is formulated to determine the first critical level of swirl at which a special mode of a non-columnar small disturbance may appear on the base flow. It is found that when the characteristic Mach number of the base flow tends to zero the eigenvalue problem and the critical swirl are the same as defined by Wang & Rusak (1996a, 1997a) in their study of incompressible swirling flows in pipes. As the characteristic Mach number is increased, the critical swirl level increases and the flow perturbation expands in the radial direction. As the Mach number is increased toward a certain limit value related to the core size of the vortex, the critical swirl reaches very large values and becomes singular. The present results indicate that the axisymmetric breakdown of high-Reynolds-number compressible vortex flows may be delayed with the increase of the flow Mach number.

Rusak, Z. and Seginer, A.

"THREE DIMENSIONAL DYNAMIC AND STATIC STABILITY OF VORTEX SYSTEMS AND THEIR OBSERVABILITY AND CONTROLLABILITY"

ICAS 1990, Paper No. 3.2.1, September 1990, Stockholm, Sweden.

A general theory for the three-dimensional long-wave linear stability of a general system of straight potential vortices immersed in an incompressible inviscid potential external flow field and in the vicinity of solid surfaces, is presented. The flow field equations are governed by the streak-line equations for the vortices and by the satisfaction of the tangency boundary condition on the solid surfaces. In their basic state, the vortices are assumed to be straight parallel filaments, near infinite two-dimensional steady surfaces that are represented by a potential source surface distribution. Small three-dimensional long wave perturbations, constructed of two orthogonal waves, are imposed on the vortex filaments, concurrently with fluctuations in the intensity of the source distribution, and with known unsteady perturbations along the shape of the solid surfaces. The singularity in the calculation of the self-induced velocity of a curved vortex line is treated by the 'Cut-off distance' model. A linearization of the flow-field equations followed by a Fourier transformation, results in a system of zero-order equations, for the two-dimensional dynamics of the vortices in their basic state, and first-order equations, that are constructed of Fredholm integral equations of the second kind for the source fluctuations distribution, and of the first-order linear differential equations that describe the time-history of the vortex perturbations. When the basic state is steady, or quasi-steady, the first-order equations result in an eigenvalue problem. Analysis shows that the perturbations development in time can never be asymptotically stable. The outcome of the model are the new concepts of 'Generalized Damping of a Vortex System' that govern its dynamic stability, and 'Rigidity' that governs the static divergence of a vortex system, which was never considered before. Also, a control approach is presented, together with the new concepts of 'Controllability' and 'Observability', that lead to the challenging idea of 'Active Control' of vortex stability.

Rusak, Z. and Wang, S.

"REVIEW OF THEORETICAL APPROACHES TO THE VORTEX BREAKDOWN PHENOMENON"

AIAA Paper No. 1996-2126, New Orleans, June 1996

We review in this paper theoretical and numerical studies of the nearly axisymmetric vortex breakdown in a pipe. Although several explanations of vortex breakdown have been proposed, a consistent description of this complicated phenomenon has not yet been provided. Also, the relations between the various theoretical and numerical solutions is not fully clear. We then describe a recent theory that has been developed by the authors. The theory is built of global analysis of the steady state solutions of the Euler equations that describe the motion of an axisymmetric and inviscid swirling flow in a pipe and of linear stability analysis of the various steady state solutions under certain boundary conditions that may reflect the physical situation. The theory unifies the major previous theoretical approaches and provides, for the first time, a consistent explanation of the physical mechanism leading to the axisymmetric vortex breakdown phenomenon, as well as the conditions for its occurrence.

Rusak, Z., Seginer, A. and Wasserstrom, E.

"CONVERGENCE CHARACTERISTICS OF A VORTEX-LATTICE METHOD FOR NONLINEAR CONFIGURATION AERODYNAMICS"

J. Aircraft, Vol. 15, No. 12, December 1978, pp. 861-863

The convergence characteristics of a vortex-lattice method for the high-angle-of-attack, nonlinear aerodynamics of aircraft and missile configurations are studied parametrically. The solution for the vortex intensities is determined by the tangency boundary condition on all of the configuration surfaces, including the three-dimensional, rolled-up wakes that characterize such flowfields. The a priori unknown position of the wake that renders this problem nonlinear is determined by an iterative process. Since there is no proof for the existence and uniqueness of this process, this paper investigates the effects of several geometrical and numerical parameters on the converged solution. It was found that the convergence of the iterative solution procedure is usually rapid and is not affected by initial conditions of the first iteration and by the integration method of the wake streamlines. Grid refinement leads to a converged solution, but its final values vary with wing surface paneling and wake discretization schemes within some range in the vicinity of the experimental data.

Rusello, P. J. and Cowen, E. A.

"TURBULENT DISSIPATION ESTIMATES FROM PULSE COHERENT DOPPLER INSTRUMENTS"

Proceedings of the IEEE/OES/CWTM Conference on Current Measurement Technology, March 2011, Monterey, CA, pp. 167-172.

Utilizing a commercially available acoustic Doppler velocimeter, the Nortek Vectrino with optional plus firmware, measurements of turbulence are made in a turbulent open channel flow in the 8m Research Flume of the DeFrees Hydraulics Laboratory. The measurements are used to estimate

dissipation from Kolmogorov's 2/3, 5/3 and 4/5 Laws as well as integration of the dissipation spectrum. Corrections to remove bias due to Doppler noise are carried out when appropriate. Results from the four methods are compared to judge the validity of each for use with single point velocity measurements from an acoustic Doppler Velocimeter. The 4/5 Law is the most consistent across each velocity component, but all methods produce reasonable estimates of dissipation from at least one velocity component.

Rutishauser, D.

"RECENT ANALYSIS AND STATUS OF DFW AND MEM WAKE VORTEX DATABASES IMPLICATIONS FOR WAKE MODELLING AND AVOSS PREDICTOR ALGORITHM REFINEMENTS"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

NASA Langley Research Center (LaRC) has collected large amounts of field data to support wake vortex research. These data include wake vortex position and strength information from a variety of research sensors, and corresponding meteorological parameters relevant to wake vortex behavior. The data was collected during field deployments from 1994 to 2000. The content and availability of the LaRC wake data will be summarized in this presentation, as well as the usefulness of the various types of data for wake modeling activities. Recent analysis of the data for wake modeling and wake mitigation concept development will also be discussed.

Rutishauser, D. K.

"PROGRESS TOWARDS THE INVESTIGATION OF TECHNICAL ISSUES RELEVANT TO THE DESIGN OF AN AIRCRAFT WAKE VORTEX ADVISORY SYSTEM (WakeVAS)"

AIAA Paper No. 2003-3808, Orlando, FL, June 2003.

Wake vortex separations applied to aircraft during instrument operations have been shown to potentially introduce inefficiencies in air traffic operations during certain weather conditions conducive to short duration wake hazards between pairs of landing aircraft. NASA Langley Research Center (LaRC) demonstrated an integration of technologies that provided real-time observations and predictions of aircraft wake behavior, from which reduced wake spacing from the current criteria was derived. To take this proof of concept to an operational prototype system, NASA has been working in cooperation with the FAA and other government and industry members to design operational concepts for a Wake Vortex Advisory System (WakeVAS). In addition to concept development, open research issues are being addressed and activities to quantify system requirements and specifications are currently underway. This paper describes the technological issues relevant to WakeVAS development and current NASA efforts to address these issues.

Rutishauser, D. K. and O'Connor, C. J.

"AIRCRAFT WAKE VORTEX SPACING SYSTEM (AVOSS) PERFORMANCE UPDATE AND VALIDATION STUDY"

NASA TM-2001-211240, October 2001, NASA Langley Research Center, Hampton, VA

An analysis has been performed on data generated from the two most recent field deployments of the Aircraft Wake VORtex Spacing System (AVOSS). The AVOSS provides reduced aircraft spacing criteria for wake vortex avoidance as compared to the FAA spacing applied under Instrument Flight Rules (IFR). Several field deployments culminating in a system demonstration at Dallas Fort Worth (DFW) International Airport in the summer of 2000 were successful in showing a sound operational concept and the system's potential to provide a significant benefit to airport operations. For DFW, a predicted average throughput increase of 6% was observed. This increase implies 6 or 7 more aircraft on the ground in a one-hour period for DFW operations. Several studies of performance correlations to system configuration options, design options, and system inputs are also reported. The studies focus on the validation performance of the system.

Rutishauser, D. K., Butler, P. and Riggins, J.

"A SENSITIVITY STUDY OF THE AIRCRAFT VORTEX SPACING SYSTEM (AVOSS) WAKE PREDICTOR ALGORITHM TO THE RESOLUTION OF INPUT METEOROLOGICAL PROFILES"

NASA TM-2004-213239, June 2004, NASA Langley Research Center, Hampton, VA

The AVOSS project demonstrated the feasibility of applying aircraft wake vortex sensing and prediction technologies to safe aircraft spacing for single runway arrivals. On average, AVOSS provided spacing recommendations that were less than the current FAA prescribed spacing rules, resulting in a potential airport efficiency gain. Subsequent efforts have included quantifying the operational specifications for future Wake Vortex Advisory Systems (WakeVAS). In support of these efforts, each of the candidate subsystems for a WakeVAS must be specified. The specifications represent a consensus between the high-level requirements and the capabilities of the candidate technologies. This report documents the beginnings of an effort to quantify the capabilities of the AVOSS Prediction Algorithm (APA). Specifically, the APA horizontal position and circulation strength output sensitivity to the resolution of its wind and turbulence inputs is examined. The results of this analysis have implications for the requirements of the meteorological sensing and prediction systems comprising a WakeVAS implementation.

Rutishauser, D., Donohue, G. L. and Haynie, R. C.

"MEASUREMENTS OF AIRCRAFT WAKE VORTEX SEPARATION AT HIGH ARRIVAL RATES AND A PROPOSED NEW WAKE VORTEX SEPARATION PHILOSOPHY"

Fifth EUROCONTROL/FAA ATM R&D Seminar, June 2003, Budapest, Hungary

This paper presents data and a proposed new aircraft wake vortex separation standard that argues for a fundamental re-thinking of international practice. The current static standard, under certain atmospheric conditions, presents an unnecessary restriction on system capacity. A new approach, that

decreases aircraft separation when atmospheric conditions dictate, is proposed based upon the availability of new instrumentation and a better understanding of wake physics.

Rutishauser, D., Donohue, G. L. and Haynie, R. C.

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This paper presents data and a proposed new aircraft wake vortex separation standard that argues for a fundamental re-thinking of international practice. The current static standard, under certain atmospheric conditions, presents an unnecessary restriction on system capacity. A new approach, that decreases aircraft separation when atmospheric conditions dictate, is proposed based upon the availability of new instrumentation and a better understanding of wake physics.

Rutishauser, D., Lohr, G., Hamilton, D., Powers, R., McKissick, B., Adams, C. and Norris, E.

"WAKE VORTEX ADVISORY SYSTEM (WAKEVAS) CONCEPT OF OPERATIONS"

NASA/TM-2003-212176, April 2003, NASA Langley Research Center, Hampton, VA

NASA Langley Research Center has a long history of aircraft wake vortex research, with the most recent accomplishment of demonstrating the Aircraft Vortex Spacing System (AVOSS) at Dallas/Fort Worth International Airport in July 2000. The AVOSS was a concept for an integration of technologies applied to providing dynamic wake-safe reduced spacing for single runway arrivals, as compared to current separation standards applied during instrument approaches. AVOSS included state-of-the-art weather sensors, wake sensors, and a wake behavior prediction algorithm. Using real-time data AVOSS averaged a 6% potential throughput increase over current standards. This report describes a Concept of Operations for applying the technologies demonstrated in the AVOSS to a variety of terminal operations to mitigate wake vortex capacity constraints. A discussion of the technological issues and open research questions that must be addressed to design a Wake Vortex Advisory System (WakeVAS) is included.

Rutten, M.

"VORTEX AXIS CALCULATION BY USING VORTEX FEATURES"

AIAA Paper No. 2004-2353, Portland, OR, June-July 2004

For the development of highly maneuverable and high angle of attack aircraft flight, an essential point is to know the structure and behaviour of the vortical flow over delta wings. Vortex breakdown is one of the limiting factors of extreme maneuvers in flight and is a significant component of flight control. The demand of simulating the vortical flow behaviour has pushed the limits of current CFD Codes, but also the demand of advanced post processing tools. From an analysis point of view, the important

requirement is the capability to identify vortical flow patterns like vortex axis lines, vortex hull surfaces, and vortex interactions. This information is significant for a deeper physical understanding of various vortical flow phenomena and for flight control of aircrafts. Therefore, one goal of this paper is to compare typical vortex identification methods applied to the vortical flow over a generic 65 degrees swept delta wing. The overall goal of this paper is to use these methods as elements of a construction kit to define a fast algorithm to detect and calculate vortex axes.

Rutten, M., Alrutz, T. and Wendland, H.

"A VORTEX AXIS AND VORTEX CORE BORDER GRID ADAPTATION ALGORITHM"

International Journal for Numerical Methods in Fluids, Vol. 58, 2008, pp. 1379-1405.

In the design process of hydrodynamical and aerodynamical technical applications, the numerical simulation of massively separated vortical flow is crucial for predicting, for example, lift or drag. To obtain reliable numerical results, it is mandatory to accurately predict the physical behavior of vortices. Thus, the dominant vortical flow structures must be resolved in detail, which requires a local grid refinement and certain adaptation techniques. In this paper, a vortex flow structure adaptation algorithm is presented, which is particularly designed for local grid refinement at vortex axes positions and associated vortex core border locations. To this end, a fast and efficient vortex axis detection scheme is introduced and the algorithm for the vortex core border determination is explained. As the interaction between vortices makes the assignment of grid points to a certain vortex axis difficult, a helicity-based vortex distinction approach in combination with a geometrical rotational sensor is developed. After describing the combined different techniques in detail, the vortex feature adaptation algorithm is applied to analytical and more realistic examples, which show that the described grid adaptation algorithm is able to enhance the grid cell resolution locally such that all significant vortical flow phenomena are resolved.

Ryan, K., Butler, C. J. and Sheard, G. J.

"STABILITY CHARACTERISTICS OF A COUNTER-ROTATING UNEQUAL-STRENGTH BATCHELOR VORTEX PAIR"

Journal of Fluid Mechanics, Vol. 696, 2012, pp. 374-401.

A Batchelor vortex represents the asymptotic solution of a trailing vortex in an aircraft wake. In this study, an unequal-strength, counter-rotating Batchelor vortex pair is employed as a model of the wake emanating from one side of an aircraft wing; this model is a direct extension of several prior investigations that have considered unequal-strength Lamb-Oseen vortices as representations of the aircraft wake problem. Both solution of the linearized Navier-Stokes equations and direct numerical simulations are employed to study the linear and nonlinear development of a vortex pair with a circulation ratio of -0.5. In contrast to prior investigations considering a Lamb-Oseen vortex pair, we note strong growth of the Kelvin mode $[-2,0]$ coupled with an almost equal growth rate of the Crow instability. Three stages of nonlinear instability development are defined. In the initial stage, the Kelvin

mode amplitude becomes sufficiently large that oscillations within the core of the weaker vortex are easily observable and significantly affect the profile of the weaker vortex. In the secondary stage, filaments of secondary vorticity emanate from the weaker vortex and are convected around the stronger vortex. In the tertiary stage, a transition in the dominant instability wavelength is observed from the short-wavelength Kelvin mode to the longer-wavelength Crow instability. Much of the instability growth is observed on the weaker vortex of the pair, although small perturbations in the stronger vortex are observed in the tertiary nonlinear growth phase.

Ryan, K., Sheard, G. J. and Thompson, M. C.

"SHORT WAVE INSTABILITIES OF COUNTER-ROTATING BATCHELOR VORTEX PAIRS"

Fifth International Conference on CFD in the Process Industries, CSIRO, December 2006, Melbourne, Australia.

Recently, investigations have considered the cooperative elliptic instability which forms by the mutual co-existence of a counter-rotating Batchelor-type vortex pair. Such vortex pairs are observed in the wake of an aircraft and pose a significant danger to trailing aircraft. An aircraft flying through the wake of a lead aircraft can exhibit significant loss of lift and control forces; several accidents and near-misses have been recorded. Our investigation has identified that short-wave Kelvin-type instabilities may prematurely destroy the vortex pair. By inducing short-wave instabilities there is the potential to significantly improve safety in the aviation industry. The work has relied heavily on CFD to validate analytical estimates and provide data for future experimental investigations.

Ryu, K.-W. and Lee, D.-J.

"SOUND RADIATION FROM ELLIPTIC VORTEX RINGS: EVOLUTION AND INTERACTION"

Journal of Sound and Vibration, Vol. 200, Issue 3, February 1997, pp. 231-252

Sound generation from the evolution and interaction of elliptic vortex rings is calculated numerically. An elliptic vortex ring emits a strong sound signal due to significant distortion and stretching of the vortex filament. At the far field, the acoustic pressure is linearly dependent on the third time derivatives of the vortex positions. Therefore, a numerical scheme of high resolution is employed to describe in detail the elliptic vortex ring motions, which are highly non-linear. Discretized vortex filaments are interpolated by using a parametric blending function to remove a possible numerical instability. The distorted vortex filament, owing to the self-induced velocity and the induced velocity from the other vortex segments, is redistributed at each time step. The accuracy and efficiency of the scheme are validated by comparisons with the analytic solution of circular vortex ring interaction. Acoustic signals from the evolution of a single elliptic vortex ring are obtained with various aspect ratios of the axes. Vortex motions and acoustic signals from two identical elliptic vortex rings, placed initially with selected separation distances, are calculated. Distinct periods are obtained from the evolution of each single elliptic vortex ring and the pairing process of two elliptic vortex rings. The calculated

periods in the acoustic signals depend to a significant degree on the initial aspect ratio of the ring and the separation distance.

Ryu, K.-W., Lee, D.-J. and Koo, S.-O.

"SOUND GENERATION DUE TO A SPINNING VORTEX PAIR NEAR THE FLAT AND CURVED WALL"

AIAA/CEAS-96-1748, State College, PA, May 1996

A numerical study of a two-dimensional acoustic field is carried out for a spinning vortex pair located near a wall to investigate the effect of the wall from the spinning quadrupole source in unsteady vortical flows. Based on the unsteady hydrodynamic information from the known incompressible flow field, the perturbed compressible acoustic terms derived from the Euler equations are calculated. Non-reflecting boundary conditions on the free field and the solid boundary conditions are developed for a generalized curvilinear coordinates system to investigate the effect of a curved wall. It is concluded that the sound generated by the quadrupole sources of unsteady vortical flows in the presence of a flat wall or a circular cylinder can be calculated by using the source terms of hydrodynamic flow fluctuations in both near and far acoustic fields simultaneously.

Saban, D.

"WAKE VORTEX MODELLING AND SIMULATION FOR AIR VEHICLES IN CLOSE FORMATION FLIGHT"

PhD Thesis, Jan. 2010, Cranfield University, Bedfordshire, UK.

The aim of this research is to develop realistic models of aerodynamic cross-coupling effects that can be incorporated in real-time or near real-time simulations of Unmanned Aerial Vehicles (UAV's) in close formation flight. These would permit the assessment of the risks and issues associated with wake vortex evolution and encounter and the analysis of their consequences on the design of automatic control systems and the development of safe and reliable operating procedures. Several wake vortex modeling techniques that can be used in formation flight simulations are reviewed. A novel Wake Vortex Model (WVM) is developed, implemented, verified, validated, and successfully integrated within a Matlab/Simulink simulation environment. The code, named ELL because it is based on Weissinger's extended lifting line theory, meets the following requirements: (i) it is generic and can easily be adapted to accommodate any wing planform and air vehicle configuration; (ii) it is computationally rapid enough to be used in real-time or near real-time simulations; (iii) and it is sufficiently representative to support studies of aerodynamic interaction between multiple air vehicles during formation reconfiguration and air-to-air refueling simulations. Simulink test scenarios of two Aerosonde UAVs are developed to test and validate the use of ELL within simulation models, and the simulation environment is interfaced with visualization tools to facilitate the evaluation of multiple air vehicle dynamic interaction.

Saban, D., Whidborne, J. F. and Cooke, A. K.

"SIMULATION OF WAKE VORTEX EFFECTS FOR UAVS IN CLOSE FORMATION FLIGHT"

The Aeronautical Journal, Vol. 113, No. 1149, 2009, pp. 727-738.

This paper addresses the development of multiple UAV deployment simulation models that include representative aerodynamic cross-coupling effects. Applications may include simulations of autonomous aerial refueling and formation flying scenarios. A novel wake vortex model has been developed and successfully integrated within a MATLAB/Simulink simulation environment. The wake vortex model is both sufficiently representative to support studies of aerodynamic interactions between multiple air vehicles, and straightforward enough to be used within real time or near real time air-to-air simulations. The model integration process is described, and computational results of a two-vehicle-formation flight are presented.

Sabelnikov, V.

"EXPERIMENTAL INVESTIGATION OF COMBUSTION STABILIZATION IN SUPERSONIC FLOW USING FREE RECIRCULATION ZONES"

Report SPC 96-4043, August 1997, Central Aerohydrodynamics Institute, Moscow, Russia.

Final report summarizes shortly main results of three quarterly reports and presents experimental results on self-ignition and combustion stabilization in supersonic flow using free circulation zone. Tests are conducted at hypersonic facility TsAGI T-131B. Measurements are performed in a nearly matched supersonic jet at the exit of two-dimensional channel over Mach number range $M = 2.0-2.8$ at stagnation temperature range $T = 1200-1400K$. Initial thickness of jet was equal 67 mm. Self-ignition and stabilization are obtained at $T = 1400K$. Self-ignition was absent at $T = 1200K, 1300K$. Thickness of free recirculation zone was about 25-30 mm.

Sabel'nikov, V. A., Korontsvit, Y. P., Ivanyushkin, A. K. and Ivanov, V. V.

"EXPERIMENTAL INVESTIGATION OF COMBUSTION STABILIZATION IN SUPERSONIC FLOW USING FREE RECIRCULATING ZONE"

AIAA Paper No. 98-1515, Jan. 1998, Reno, NV.

The paper presents experimental results on self-ignition and combustion stabilization of aerated by gas liquid kerosene in supersonic flow using free recirculating zone which was generated by the interaction of a concentrated vortex with a normal shock wave. Tests were conducted in hypersonic facility of TsAGI T-131B in a nearly matched to atmospheric pressure supersonic jet at the exit of two-dimensional channel over Mach number range $M = 2.0-2.8$ and total temperature range $T = 1200-1400K$. Initial thickness of jet was equal 67 mm. Self-ignition was not achieved at $T = 1400K$ and $1300K$. Thickness of free circulating zone was about 25-30 mm.

Saberi, H. A.

"ANALYTICAL MODEL OF ROTOR WAKE AERODYNAMICS IN GROUND EFFECT"

NASA-CR-166533, Stanford University, December 1983

The model and the computer program developed provides the velocity, location, and circulation of the tip vortices of a two-blade helicopter in and out of the ground effect. Comparison of the theoretical results with some experimental measurements for the location of the wake indicate that there is excellent accuracy in the vicinity of the rotor and fair amount of accuracy far from it. Having the location of the wake at all times enables us to compute the history of the velocity and the location of any point in the flow. The main goal of our study, induced velocity at the rotor, can also be calculated in addition to stream lines and streak lines. Since the wake location close to the rotor is known more accurately than at other places, the calculated induced velocity over the disc should be a good estimate of the real induced velocity, with the exception of the blade location, because each blade was replaced only by a vortex line. Because no experimental measurements of the wake close to the ground were available, quantitative evaluation of the theoretical wake was not possible. But qualitatively we have been able to show excellent agreement. Comparison of flow visualization with our results has indicated the location of the ground vortex is estimated excellently. Also the flow field is, however, well represented.

Sacks, A. H.

"BEHAVIOR OF VORTEX SYSTEM BEHIND CRUCIFORM WINGS - MOTIONS OF FULLY ROLLED-UP VORTICES"

NACA TN-2605, January 1952, Langley Aeronautical Laboratory, Langley Field, VA.

The motions of four fully rolled-up vortices representing the vortex system trailing behind cruciform wings are studied by theoretical and visual-flow methods. The analysis applies throughout the Mach number range. Equations are developed for the three-dimensional paths traced by the vortices behind a cruciform wing banked 45 deg., and calculations are made of the distance behind the wing at which the upper two vortices pass through the lower two. It is found that this 'leapfrog' distance depends upon the lift coefficient, aspect ratio, and span loading of the cruciform wing, and that for low-aspect-ratio cruciform wings leapfrogging may occur within two chord lengths of the trailing edges. The various types of vortex motion to be expected throughout the angle-of-attack range are considered in some detail, and the interaction of the two vortex sheets shed from the cruciform wing is taken into account. Results of some water-tank studies are also presented and compared with the theory.

Saffman, P. G.

"STRUCTURE AND STABILITY OF STREETS OF FINITE VORTICES"

Vortex Motion: Proceedings of a Colloquium Held at Goettingen on the Occasion of the 75th Anniversary of the Aerodynamische Versuchsanstalt in November 1982, edited by Hornung, H. G. and E. A. Muller

Results are presented for the steady motion of finite cored uniform vortices in an incompressible perfect fluid. The cases of single vortices, vortex pairs, single rows and the staggered double row are considered. The stability of the flows to two-dimensional disturbances is examined. In particular, it is shown that finite area stabilizes the Karman vortex street for a finite band of aspect ratio values about the Karman value of 0.281.

Saffman, P. G.

"THE VELOCITY OF VISCOUS VORTEX RINGS"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 9-10

The motion of vortex rings of small cross section is considered. A formula is given for the velocity of a ring in an ideal fluid with an arbitrary distribution of vorticity in the core and an arbitrary circumferential velocity. A definition of velocity is given for the unsteady diffusing ring in a viscous fluid, and the speed is found by the method used for rings in ideal fluids.

Saffman, P. G.

"THE MOTION OF A VORTEX PAIR IN A STRATIFIED ATMOSPHERE"

Studies in Appl. Math., June 1972, Vol. 51, No. 2, pp. 107-119

The movement of a horizontal vortex pair through an inhomogeneous fluid is considered. The problem is formulated first for the case when the ambient fluid is uniform, the fluid moving with the vortex pair has a different density, and the motion is supposed laminar and inviscid. An approximate solution is obtained, which predicts that the distance between the vortices stays constant and the vortices accelerate at a constant rate. This solution is then applied to motion in a stratified atmosphere and it is found that the vortices oscillate vertically with a frequency and amplitude depending on the initial conditions and the stratification. Finally, approximate equations are constructed to describe the effects of turbulent entrainment into the fluid moving with the vortex pair, and an estimate of the damping is obtained.

Saffman, P. G.

"THE STRUCTURE OF TURBULENT LINE VORTICES"

AFOSR-72-2283, October 1972, California Institute of Technology, Pasadena, CA

A theory is given to explain the observed dependence on Reynolds number of the decay of turbulent line vortices. The discussion considers first the self-similar vortex, in which all quantities are assumed to depend only on the circulation at infinity, the Reynolds number, and the time from a virtual origin. It is argued that the turbulent line vortex has a triple structure: an outer vortex of given radius, an inner vortex, and a viscous core. The axial velocity in the core, produced by growth of a trailing vortex, is shown to be Reynolds number dependent.

Saffman, P. G.

"STRUCTURE OF TURBULENT LINE VORTICES"

Phys. Fluids, Vol. 16, No. 8, August 1973, pp. 1181-1188

A theory is given to explain the observed dependence on Reynolds number of the decay of turbulent line vortices. It is argued that the turbulent vortex has a triple structure; an outer region with a logarithmic distribution of circulation; and an inner region and viscous core in both of which the motion is close to solid body rotation. The development of an overshoot of circulation in the outer region is discussed, and the axial velocities produced by growth of a trailing vortex are calculated.

Saffman, P. G.

"A MODEL OF VORTEX RECONNECTION"

J. Fluid Mech., Vol. 212, March 1990, pp. 395-402

A model is proposed to describe the breaking and rejoining of vortex lines which occurs when vortex filaments of equal and opposite strengths touch. It is based on the idea that viscosity cancels the vorticity where the filaments first touch. The weakening of the centrifugal force in the vortex core then leads to a local increase in the pressure which accelerates the fluid in the cores in the axial direction and convects the vorticity away from the initial contact and produces an apparent rejoining.

Saffman, P. G.

"VORTEX DYNAMICS"

Cambridge Monographs on Mechanics and Applied Mathematics, 1st edition, Cambridge University Press, New York, 1992

The emphasis in this monograph is on the classical theory of inviscid incompressible fluids containing finite regions of vorticity. The effects of viscosity, compressibility, inhomogeneity, and stratification are enormously important in many fields of application, from hypersonic flight to global environmental fluid mechanics. However, this volume focuses on those aspects of fluid motion which are primarily controlled by the vorticity and are such that the effects of the other fluid properties are secondary.

Saffman, P. G.

"APPROACH OF A VORTEX PAIR TO A RIGID FREE SURFACE IN VISCOUS FLUID"

Physics of Fluids, A - Fluid Dynamics, Vol. 3, No. 5, Pt. 1, May 1991, pp. 984-985

The motion in a viscous incompressible fluid of a vortex pair toward a rigid plane wall on which slip is allowed is considered. It is shown that the centroids of vorticity do not approach the wall monotonically, and there is some rebound at a rate depending upon the viscosity and initial separation of the vortices.

Saffman, P. G. and Schatzman, J. C.

"AN INVISCID MODEL FOR THE VORTEX-STREET WAKE"

Journal of Fluid Mechanics, Vol. 122, 1982, pp. 467-486.

An inviscid model for the Karman vortex street, containing vortices of uniform vorticity surrounded by irrotational fluid, is related to the wake behind a bluff body by a global analysis requiring the conservation of momentum, energy and vorticity. Some comparison is made with experimental results reported in the literature. A qualitative procedure is proposed whereby the slow evolution of the wake through viscous effects is approximated. Some comments are made regarding the relevance of the stability properties of the inviscid street. Some calculations are made for the 'secondary vortex street' that is observed after breakdown and rearrangement, and comparison is made with experiment.

Saito, T. and Takagi, M.

"WAKE SURVEY OF AN AIRPLANE MODEL WITH AND WITHOUT GROUND PLANE"

Proceedings of 9th International Symposium on Flow Visualization, Edinburgh, Scotland, August 2000, pp. 349-1 - 349-4

The tip vortices at the ends of the wing and the flap of a model airplane are investigated. The methods are force measurements and wake surveys. The balance is a strut type six component balance and the wake survey is done by a traversing rake of four simple total pressure (Pitot) probes. The measurements are carried out at various combinations of the angle of attack, the flap, and the ground plane. The results clearly show the relationship between aerodynamic characteristics and the flow field, and a possibility to improve the flap efficiency was suggested.

Sakamaki, H., Wakayama, T., Tanaka, H., Sekiguchi, T. and Hirano, Y.

"DEVELOPMENT OF A WAKE VORTEX DETECTION ALGORITHM USING COHERENT LASER RADAR"

13th CLRC Proceedings, Oct. 2005, Tokyo, Japan, pp. 148-151

In the present paper, we have proposed a wake vortex detection algorithm using the template matching method. And the computer simulations with Doppler velocity distributions of the pseudo wake vortex have borne out that the proposing method operated properly. We have developed a wake vortex detection system using coherent laser radar, and have been evaluating this algorithm.

Salas, M. D. and Kuruwila, G.

"STUDY OF THREE-DIMENSIONAL EFFECTS ON VORTEX BREAKDOWN"

ICAS 1988, Paper No. 5.4.2, August-September 1988, Jerusalem, Israel.

The incompressible, axisymmetric, steady Navier-Stokes equations in primitive variables are used to simulate vortex breakdown. The equations, discretized using a second-order, central-difference scheme, are linearized and then solved using an exact LU decomposition, Gaussian elimination, and Newton iteration. Solutions are presented for Reynolds numbers, based on vortex-core radius, as high as 1500. An attempt to study the stability of the axisymmetric solutions to three-dimensional perturbations is discussed.

Samant, S. S. and Gray, R. B.

"A SEMI-EMPIRICAL CORRECTION FOR THE VORTEX CORE EFFECT ON HOVERING ROTOR WAKE GEOMETRIES"

33rd Annual National V/STOL Forum of the American Helicopter Society, Washington, DC, May 1977

A semi-empirical correction for the vortex core effect on hovering rotor wake geometries is presented. The results show that with this effect included, the tip vortex geometry in the near wake can be calculated with much better accuracy for one-, two-, three-, and four-bladed rotors than has been previously possible. The method breaks down for six-bladed rotors and this appears to be due to the use of the lifting line rather than the lifting surface model for the blade.

Samet, M. and Einav, S.

"MEAN VALUE MEASUREMENTS OF A TURBULENT SWIRLING-JET"

AIAA Journal, Vol. 26, No. 5, May 1988, pp. 619-621.

Our knowledge of the swirling-jet in a coflowing stream is quite limited. The present study is an attempt to provide sufficiently complete and reliable information on swirling-jets in still and moving surroundings. The data obtained during the present study were restricted to mean values in the swirling-jet. The data showed that the longitudinal and radial distributions of mean-velocity components were strongly affected by the degree-of-swirl and velocity ratio.

Sammonds, R. I. and Stinnett, Jr., G. W.

"HAZARD CRITERIA FOR WAKE VORTEX ENCOUNTERS"

NASA TM X-62473, August 1975, NASA Ames Research Center, Moffett Field, CA

A piloted, motion-based simulation was conducted to evaluate the ability of simulators to produce realistic vortex encounters and to develop criteria to define hazardous encounters. A boundary for

encounter hazard based on subjective pilot opinion could be identified in terms of maximum bank angle. For encounter altitudes from 200 to 500 feet, tentative hazard criteria established for visual flight conditions indicated that the acceptable upset magnitude increased nearly linearly with increasing altitude.

Sammonds, R. I., Stinnett, Jr., G. W. and Larsen, W. E.

"WAKE VORTEX ENCOUNTER HAZARDS CRITERIA FOR TWO AIRCRAFT CLASSES"

FAA-RD-75-206, June 1976, NASA Ames Research Center, Moffett Field, CA

An investigation was conducted using a piloted, motion-base simulator to determine wake vortex hazard criteria for two classes of jet transport aircraft. A light business jet and a large multiengine jet transport were represented respectively. The hazard boundaries were determined in terms of the maximum bank angle due to the vortex encounter. Upsets as small as 7 deg in bank angle were considered to be hazardous at breakout altitude (200 ft (61.0 m)) for Instrument Flight Rule (IFR) and at 50 ft (15.2 m) for Visual Flight Rule (VFR) for both aircraft classes. Proximity to the ground was the primary reason for a hazardous rating. This was reflected in the reduction in the maximum bank angle at the hazard boundary and in more consistent ratings as altitude was decreased.

Sammonds, R. I., Stinnett, Jr., G. W. and Larsen, W. E.

"CRITERIA RELATING WAKE VORTEX ENCOUNTER HAZARD TO AIRCRAFT RESPONSE"

J. Aircraft, Vol. 14, No. 10, October 1977, pp. 981-987

Piloted six-degree-of-freedom motion simulator investigations were conducted at the NASA Ames Research Center to determine criteria relating the hazard posed by a wake vortex encounter to the response of the encountering airplane. These investigations demonstrated that wake vortex encounters can be reproduced realistically on a simulator, established that the maximum bank angle due to the encounter provides the best correlation with the pilot's subjective assessment of the hazard, and determined hazard boundaries in terms of maximum bank angle for two classes of jet transport aircraft.

Sampson, R. G.

"AN EXPERIMENTAL AND THEORETICAL INVESTIGATION OF THE STRUCTURE OF A TRAILING VORTEX WAKE"

Aviation Quarterly, Vol. 3, February 1977, pp. 39-50.

An improved technique for the use of a five-hole yaw probe has been used in determining velocity, vorticity, and pressure distributions over a transverse plane five chords downstream of a lifting wing. A well-defined tip vortex is shown to exist, together with a vortex sheet which contains a significant proportion of the total vorticity. The vorticity distribution is compared with that predicted by the

calculation of vortex sheet roll-up using a two-dimensional array of line vortices. Good agreement is obtained, and the validity of using time steps large enough to inhibit the chaotic motion found in some calculations of this type is demonstrated. The structure of the tip vortex is found to be well described by the turbulent vortex model of Hoffman and Joubert.

Sampson, R. G.

"TRAILING VORTEX WAKE STRUCTURE"

In: Deutsche Gesellschaft fuer Luft- und Raumfahrt, European Rotorcraft and Powered Lift Aircraft Forum, 2nd, Bueckeburg, W. Germany, September 20-22, 1976

The wake trailed by a half-wing mounted in an open-jet wind tunnel has been studied over a transverse plane five chords downstream. Vorticity contours show a well-defined tip vortex, together with a diffuse vortex sheet which contains a significant portion of the circulation. Calculations of the roll-up of a sheet of line vortices is shown to represent the shape of the experimental vorticity contours, and the tip vortex strength, very well. In addition, the velocity distribution within the tip vortex is shown to compare well with a logarithmic circulation distribution for a turbulent line vortex.

Sanders, N. D. and Stockman, N. O.

"NOISE FROM TWO-DIMENSIONAL VORTICES"

AIAA Paper No. 1972-0155, San Diego, CA, January 1972.

The fluctuating flow in an idealized model of a turbulent shear layer composed of many discrete vortices is analyzed. Computer solutions reveal irregular motions which are similar in many respects to observed flows in turbulent three-dimensional layers. The model is further simplified to a pair of equal co-rotating vortices and the noise generation is analyzed in terms of equivalent quadrupole oscillations. Results of the analysis in a uniform medium are consistent with Lighthill's results. New results are obtained for the effects of mean velocity gradients, compressibility, temperature inhomogeneities, and gradients of the mean Mach number.

Sanderse, B.

"AERODYNAMICS OF WIND TURBINE WAKES -- LITERATURE REVIEW"

ECN-E-09-016, 2009, Energy Research Centre of the Netherlands, Petten, The Netherlands.

This report reviews the available literature on the aerodynamics of wind turbines and wind farms. Firstly, two introductory chapters are devoted to the physics of the flow around a wind turbine and the existing engineering models for blade and wake aerodynamics. The focus of this work is however on the numerical modeling of wakes. The difficulties in solving the Navier-Stokes equations are discussed, and the different existing models for the description of the rotor and the wake are mentioned, along with problems associated with the choice of turbulence models and inflow conditions. The purpose of

this overview is to include the latest developments in the numerical computation of wind turbine aerodynamics.

Sankar, L. N and Yang, Z.

"RECENT IMPROVEMENTS TO MODELING ROTOR WAKES IN HOVER AND FORWARD FLIGHT"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

The goal of this study is to develop an efficient solution methodology that will accurately predict the aerodynamic loads on a rotor in forward flight. The model should simulate the complex blade dynamic motion in forward flight, include a trim process, have a self-consistent wake model, and account for the aeroelastic deformations of the blade. A hybrid method is used in this study, and is demonstrated to be an appropriate phenomenological methodology for capturing the unsteady flow phenomena over the rotor in different flow regions. A Navier-Stokes analysis is used for modeling the viscous flow and near wake in a small region surrounding the single rotor blade. A finite volume form of the Navier-Stokes equations is solved using Roe's approximate Riemann solver with third order or fifth order spatial accuracy. In the outer zones of the computational domain, a potential flow analysis is used to solve the inviscid isentropic flow and carry the acoustic and pressure waves generated by the blade to the far field. A velocity decomposition approach is implemented that consists of a superposition of the freestream velocity, disturbance potential velocity, and induced velocity caused by the far wake. The grid velocity terms in the viscous and inviscid zones are implemented in a general form to consider the fact that the cell faces are moving with respect to an inertial observer, and are deforming because of aeroelastic effects in forward flight. A Lagrangean wake approach is implemented to capture the effects of the tip vortex once it leaves the viscous zone, and convect it without diffusion in the inviscid zone and the far field. The present approach is complete in that there is no need to link the analysis to an external rotor wake simulation code to include the far wake effects. This transonic, potential-based method with a Lagrangean wake model can convect the wake vorticity in the far field without numerical dissipation. This strategy also permits the use of a sparse grid in the far wake.

Sant, T., van Kuik, G. A. M., Haans, W. and van Bussel, G. J. W.

"AN APPROACH FOR THE VERIFICATION AND VALIDATION OF ROTOR AERODYNAMICS CODES BASED ON FREE-WAKE VORTEX METHODS"

31st European Rotorcraft Forum, September 2005, Florence, Italy, pp. 56.1-56.15.

This paper presents an approach to verify and validate a newly developed free-wake lifting line vortex code to model the wake generated by a wind turbine in axial flow conditions. Although the code is intended to simulate wind turbine wakes, it may be readily applied to propellers and helicopter rotors. The Delft University of Technology model wind turbine is used for this case study. Detailed hot-film inflow measurements in the near wake and smoke visualizations of tip vortex cores are used as a basis for validating the free-wake model. A parametric analysis was carried out to investigate how different

levels of blade/wake discretizations and viscous modeling influence the accuracy of the inflow results. The tip vortex locations were compared with those predicted by the vortex model. In general, very good agreement was obtained. It was found that the middle sections of the blades are rather insensitive to the choice of the viscous modeling parameters. However, high sensitivity to these parameters was observed at the blade tip and root regions.

Sarasua, L. G., Schifino, A. C. S. and Gonzalez, R.

"THE DEVELOPMENT OF HELICAL VORTEX FILAMENTS IN A TUBE"

Physics of Fluids, Vol. 17, April 2005, pp. 044104-1-044104-9

We study the formation of helical vortex filaments in a tube. The helical flow is assumed to be potential except in a very slender core. The boundary conditions are satisfied by introducing a helical image vortex. By assuming an axisymmetric flow upstream and imposing conservation laws, we obtain a set of conditions that must be satisfied by the helical flow downstream. We obtain that, when a generalized swirl parameter reaches a critical value, a bifurcation occurs and there are two solutions for the helical filamentary vortex. Such a bifurcation can be produced by increasing the swirl level of the inlet flow or the radius of the outlet tube, in agreement with experiments. We have discussed the influence of the core size and the Reynolds number on the generalized swirl parameter and with these results we have explained some experimental observations.

Sarpkaya, T.

"TOWARDS THE CREATION OF A PHYSICS-BASED GROUND EFFECT MODEL"

AIAA Paper No. 2006-1072, Reno, NV, January 2006

It has been evident for quite some time that the development of a physics-based real-time prediction algorithm depends on the aircraft, on a clear understanding of the characteristics of the resulting vortices, atmospheric input, and the prevailing (unsteady, turbulent) boundary layer on the ground. The previous efforts on vortices have been directed towards the design of a single velocity-profile (valid within some probabilistic limits), regardless of the type of the originating aircraft. The IGE models were based on the use of several discrete vortices or many particles to mimic the field tests. These efforts led to satisfactory comparisons (mostly with flights out of ground effect) between the model predictions and the generating aircraft, but lacked physics. The present paper introduces two radically different concepts regarding the modeling of the aircraft vortices and the ground effect in view of several facts: the vortices of all aircraft are not created equal, the orbiting of secondary and tertiary vortices around the primary vortex in ground effect has never been observed in the field, and the physics content of the existing models leaves much to be desired. It is hoped that the concepts advanced herein will enhance the accuracy of the definition of the vortices entering the ground effect, the quantification of the turbulent boundary layer (or the displacement thickness), and the physics content of the IGE models.

Sarpkaya, T.

"COMPUTATIONAL METHODS WITH VORTICES -- THE 1988 FREEMAN SCHOLAR LECTURE"

Journal of Fluids Engineering, Vol. 111, March 1989, pp. 5-52.

A comprehensive review is presented of the computational methods based upon Helmholtz's powerful concepts of vortex dynamics, making use of Lagrangian or mixed Lagrangian-Eulerian schemes, the Biot-Savart law or the Vortex-in-Cell methods. The ingenious approximations and smoothing schemes developed in search of predictive models, qualitative solutions, new insights, or just some inspiration in the simulation of often two-dimensional, occasionally three-dimensional, and almost always incompressible fluids are described in detail. The challenge is to produce results in the face of ever accumulating errors within a time scale appropriate for the investigation. The review is organized around two major sections: Theoretical foundations and practical applications of vortex methods.

Sarpkaya, T.

"AN EXPERIMENTAL INVESTIGATION OF THE VORTEX-BREAKDOWN PHENOMENON"

NPS-59SL0071A, July 1970, Naval Postgraduate School, Monterey, CA.

The results of an experimental investigation of the characteristics of stationary and travelling vortex breakdowns in swirling flow in a diverging cylindrical tube are presented and discussed. Basically, three types of vortex breakdown were observed, viz, double helix, spiral and axisymmetric breakdown. The type and location of the stationary breakdowns were found to be dependent upon the Reynolds and circulation numbers of the flow. The breakdown bubble responded to gradual and abrupt changes in the upstream and downstream flow conditions in a manner analogous to the hydraulic jump in open-channel flow. The observations reported and the evidence presented herein revealed unmistakably that the vortex breakdown is a finite transition from a uniform state of swirling flow (supercritical) to one (subcritical) featuring a large standing wave, followed by standing wavelets, of finite amplitude.

Sarpkaya, T.

"TURBULENT VORTEX BREAKDOWN"

Phys. Fluids, Vol. 7, No. 10, October 1995, pp. 2301-2303.

Reported herein is a cone-shaped turbulent vortex breakdown in noncavitating swirling flows at high Reynolds numbers in a slightly diverging cylindrical tube. The turbulent conical form is in addition to the well-known double-helix, spiral, and nearly axisymmetric or 'bubble'-type breakdowns.

Sarpkaya, T.

"DECAY OF WAKE VORTICES OF LARGE AIRCRAFT"

AIAA Paper No. 1998-0592, January 1998, Reno, NV.

A summary of the previous works is followed by an in-depth analysis of velocities, circulations, and decay histories of several trailing vortices generated by large aircraft during field tests in Memphis, TN. The results suggest that the decay of trailing vortices is governed by the mutual straining of vortices; intermittent exchange of mass, momentum, and vorticity across the core boundary; rotational damping and restructuring of turbulence in the core; stretching of large turbulent structures, turbulent diffusion, the interaction of oppositely-signed vorticity in the overlapping regions of the vortex pair, and the draining of vorticity from the Kelvin oval.

Sarpkaya, T.

"EFFECT OF CORE SIZE ON THE RISE AND DEMISE OF TRAILING VORTICES"

NPS-69-82-010, December 1982, Naval Postgraduate School, Monterey, CA.

Experiments were conducted with five lifting surfaces to investigate the evolution of trailing vortices in stratified and unstratified water. The vortex trajectories were determined as a function of the relative depth, normalized time, stratification parameter, and the relative vortex core size. The results have shown that the vortices rise only to a finite height as they gradually demise under the influence of turbulence, sinusoidal instability, and vortex breakdown. The effect of stratification is to reduce the lifespan of vortices and the maximum height attained by them. Various approximate analyses have been examined and new ones have been proposed to determine the lifespan of the trailing vortices.

Sarpkaya, T.

"ON STATIONARY AND TRAVELLING VORTEX BREAKDOWNS"

J. Fluid Mech., Vol. 45, No. 3, February 1971, pp. 545-559

This paper describes some experiments in swirling flows in a diverging cylindrical tube in which various types of vortex breakdowns were observed. In one set of experiments, the position of the breakdown, axial component of the velocity of the vortex core, swirl angle distribution ahead of the breakdown, and the pressure distribution along the tube were determined for various flow rates for various values of circulation imparted to the fluid (water). Basically, three types of vortex breakdown were observed, viz. mild (double helix) breakdown, spiral breakdown (followed by turbulent mixing), and axisymmetric breakdown (followed by a thicker vortex core, then a spiral breakdown, and finally turbulent mixing). The type and the location of the stationary breakdowns were found to be dependent, for the vortex tube being used, upon the Reynolds and circulation numbers of the flow. In a spiral breakdown, the vortex core filament maintained the same sense of rotation as the upstream fluid elements. In an axisymmetric breakdown, the bubble included an inclined vortex-ring axis gyrated about the axis of the tube.

Sarpkaya, T.

"VORTEX BREAKDOWN IN SWIRLING CONICAL FLOWS"

AIAA Journal, Vol. 9, No. 9, September 1971, pp. 1792-1799

This paper describes some experiments in swirling flows in a mildly diverging cylindrical tube in which three types of vortex breakdown were observed: double-helix and spiral forms (followed by turbulent mixing), and axisymmetric form (often followed by a spiral breakdown, then by turbulent mixing). The type and location of the breakdowns were found to be dependent upon the Reynolds and circulation numbers of the flow. The observations reported and the evidence presented herein revealed that the axisymmetric breakdown is basically a finite transition between two separate states of flow, from a uniform state of swirling flow (supercritical) to one (subcritical) featuring a series of standing waves of finite amplitude. The double-helix and spiral forms, which occur in a region well defined by Reynolds and circulation numbers, appear to be a consequence of the instability of the vortical viscous flow to spiral disturbances.

Sarpkaya, T.

"EFFECT OF THE ADVERSE PRESSURE GRADIENT ON VORTEX BREAKDOWN"

AIAA Journal, Vol. 12, No. 5, May 1974, pp. 602-607

The present work examines in detail the effect of the degree of divergence on the type and location of the vortex breakdown in swirling flows in tubes of various angles of divergence, compares the results with those predicted using the analytical models proposed by Randall and Leibovich and by Mager, and illustrates the role played by the flow separation and reversal on the tube wall.

Sarpkaya, T.

"TRAILING VORTICES IN HOMOGENEOUS AND DENSITY-STRATIFIED MEDIA"

J. Fluid Mech., Vol. 136, November 1983, pp. 85-109

Experiments were conducted with three delta wings and two rectangular wings to investigate the evolution of trailing vortices in stratified and unstratified water. The vortex trajectories were determined as a function of the normalized time Vt/b , stratification parameter Nb/V and an effective vortex-core size r/b . The results have shown that the vortices rise only to a finite height as they decay gradually at first and rapidly thereafter under the influence of turbulence, sinusoidal instability, and core bursting. The effect of stratification is to reduce the lifetime of vortices and the maximum height attained by them.

Sarpkaya, T.

"DECAY OF WAKE VORTICES OF LARGE AIRCRAFT"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 61-74

Some of the data obtained during the Memphis Field Program has been evaluated. The results suggest that the decay of trailing vortices is governed by the mutual straining of vortices; intermittent exchange of mass, momentum, and vorticity across the core boundary; turbulent diffusion; and the stretching of large turbulent structures. The molecular diffusion is inconsequential and inconsistent with the time scales and the high Reynolds numbers encountered.

Sarpkaya, T.

"DECAY OF WAKE VORTICES OF LARGE AIRCRAFT"

AIAA Journal, Vol. 36, No. 9, September 1998, pp. 1671-1679

A summary of the previous works is followed by an in-depth analysis of velocities, circulations, and decay histories of several trailing vortices generated by large aircraft during field tests in Memphis, TN. The results suggest that the decay of trailing vortices is governed by the mutual straining of vortices; intermittent exchange of mass, momentum, and vorticity across the core boundary; rotational damping and restructuring of turbulence in the core; stretching of large turbulent structures, turbulent diffusion, the interaction of oppositely-signed vorticity in the overlapping regions of the vortex pair, and the draining of vorticity from the Kelvin oval.

Sarpkaya, T.

"THREE-DIMENSIONAL INTERACTIONS OF VORTICES WITH A FREE SURFACE"

AIAA Paper No. 1992-0059, Reno, NV, January 1992

The interaction of a single turbulent trailing vortex and its image with a deformable free surface has been undertaken for the purpose of exploring the origins of scars, striations, and three-dimensional instabilities. The experiments were conducted in a low turbulence water tunnel through the use of various vertically-mounted hydrofoils. The distance between the top of the test foil and the water surface was systematically varied. The principal measurements were photographic observations of the vortices and free surface through the use of laser induced fluorescence. Certain unusual characteristics of the vortex - evolution of U-shaped structures and turbulent patches - and their role in the creation of whirls have been investigated. The numerical part of the investigation used the vortex dynamics and explored the evolution of whirls, energy spectrum, and the fractal dimensions of the two-dimensional turbulence field.

Sarpkaya, T.

"NEW MODEL FOR VORTEX DECAY IN THE ATMOSPHERE"

J. Aircraft, Vol. 37, No. 1, January-February 2000, pp. 53-61

1889

A new vortex decay model for the prediction of the descent of aircraft trailing vortices subjected to realistic environmental conditions (stratification, turbulence, crosswind, headwind, shear effects, and ground effect) is presented, and the model is applied to field data obtained with Lidar in Memphis and Dallas-Fort Worth airports. Although the model has not yet been fully optimized, the predictions and field data compare reasonably well. Some flights, particularly in unstable environments, exhibit behavior unexplainable in terms of the assumed, measured, and/or indirectly calculated input parameters, for example, vortex separation, uncertainties in Lidar measurements, stratification, shear, gravity currents, head- and crosswinds, turbulent kinetic energy, and/or the eddy dissipation rate.

Sarpkaya, T.

"A NEW MODEL FOR VORTEX DECAY IN THE ATMOSPHERE"

AIAA Paper No. 1999-0761, Reno, NV, January 1999.

The purpose of this paper is (a) to present a new vortex decay model for the prediction of the descent of aircraft trailing vortices subjected to realistic environmental conditions (stratification, turbulence, cross wind, headwind, shear effects, and ground effect), and (b) to apply the model to field data obtained with Lidar in Memphis and Dallas-Fort Worth airports. Although the model has not yet been optimized, the predictions and field data compare reasonably well. Some flights, particularly in unstable environments, exhibit behavior unexplainable in terms of the assumed, measured and/or indirectly-calculated input parameters (e.g., vortex separation, uncertainties in Lidar measurements, stratification, shear, head and cross winds, turbulent kinetic energy and/or the eddy dissipation rate.

Sarpkaya, T. and Daly, J. J.

"EFFECTS OF AMBIENT TURBULENCE AND STRATIFICATION ON THE DEMISE OF TRAILING VORTICES"

NPS69-86-006, July 1986, Naval Postgraduate School, Monterey, CA.

A series of experiments was carried out with two streamlined foils at different speeds in a towing tank. The ambient turbulence (nearly isotropic) was generated by means of a bi-planar grid. The model-grid separation distance was varied systematically in order to subject the trailing vortices to varying degrees of turbulence. The data have been expressed in terms of a normalized turbulence parameter and the relative rise of the vortices. The results have shown that the ultimate height to which the vortices rise prior to their demise is controlled by the two parameters cited, irrespective of the shape and the aspect ratio of the lifting surfaces. A numerical analysis has been initiated to analyze the motion of the trailing vortices and the propagation of internal waves in density stratified medium with the ultimate objective of incorporating the effect of turbulence into the numerical model.

Sarpkaya, T. and Daly, J. J.

"EFFECT OF AMBIENT TURBULENCE ON TRAILING VORTICES"

J. Aircraft, Vol. 24, No. 6, June 1987, pp. 399-404

The effects of ambient turbulence (generated by a biplanar grid) on the migration and lifespan of trailing vortices are investigated in a towing tank using two NACA-0012 foils moving at a constant angle of attack. The results show that the rise and demise of the vortices are controlled primarily by the rate of dissipation of the background turbulence. The integral scale of turbulence plays only a minor role. In both a quiescent or weakly-turbulent fluid the sinusoidal instability and in a fluid with stronger turbulence, the vortex bursting precedes the subsequent instability events which brings about the eventual destruction of the vortices. Both forms of the large-scale instability are often accompanied by the roll of the vortex pair onto its side. Shear is not necessary for the roll but may enhance it under atmospheric conditions.

Sarpkaya, T. and Henderson Jr., D. D.

"SURFACE DISTURBANCES DUE TO TRAILING VORTICES"

NPS-69-84-004, March 1984, Naval Postgraduate School, Monterey, CA.

The characteristics of the surface signatures resulting from the interaction of the trailing vortices with the free surface have been investigated both theoretically and experimentally. The vortices were created using three lifting surfaces of different shape and aspect ratio (two Delta wings and a rectangular foil). The surface disturbances have been classified into two groups (striations and scars) and the evolution of each type has been expressed in terms of the governing parameters such as the depth of generation of vortices, mutual induction velocity, and the initial vortex spacing. It has been shown that the surface signatures are a consequence of the strain field resulting from the nonuniform surface-velocity distribution and that they are not simple capillary-gravity waves. A turbulence model has been used to establish reasonable correlation between the theoretical and experimental results.

Sarpkaya, T. and Johnson, S. K.

"EVOLUTION OF AIRCRAFT TRAILING VORTICES IN A STRATIFIED FLUID"

AIAA Paper No. 1983-0564, Reno, NV, January 1983

The evolution of trailing vortices in stratified and unstratified water was experimentally investigated for the cases of two rectangular and three delta wings, determining vortex trajectories as a function of relative depth, normalized time, stratification parameter, and relative vortex core size. Results obtained show that vortices rise only to a finite height as they gradually decay under the influence of turbulence, sinusoidal instability, and vortex breakdown, where the effect of stratification is to reduce vortex lifespan and maximum attained height. The determination of trailing vortex lifespan is attempted through several approximate analyses.

Sarpkaya, T. and Johnson, S. K.

"TRAILING VORTICES IN STATIFIED FLUIDS"

NPS-69-82-003, June 1982, Naval Postgraduate School, Monterey, CA

Experiments were conducted with two delta wings and a streamlined body with lifting surfaces to investigate the evolution of turbulent trailing vortices in stratified and unstratified water. The vortex trajectories were determined as a function of the relative depth, normalized time, and the stratification parameter. The results have shown that the vortices rise only to a finite height as they gradually demise under the influence of turbulence, sinusoidal instability, and the vortex breakdown. The effect of stratification is to reduce the lifespan of vortices and the maximum height attained by them. Various approximate analyses have been examined and new ones have been proposed to determine the lifespan of the vortices. Finally, an exploratory numerical analysis of the two-dimensional, unsteady laminar vortices has been carried out with encouraging results.

Sarpkaya, T. and Suthon, P.

"INTERACTION OF A VORTEX COUPLE WITH A FREE SURFACE"

Experiments in Fluids, Vol. 11, 1991, pp. 205-217.

The characteristics of three-dimensional flow structures (scars and striations) resulting from the interaction between a heterotrophic vortex pair in vertical ascent and a clean free surface are described. The flow features at the scar-striation interface (a constellation of whirls or coherent vortical structures) are investigated using flow visualization, a motion analysis system, and the vortex-element method. The results suggest that the striations are a consequence of the short wavelength instability of the vortex pair and the helical instability of the tightly spiraled regions of vorticity. The whirls result from the interaction of striations with the surface vorticity. The whirl-merging is responsible for the reverse energy cascade leading to the formation and longevity of larger vortical structures amidst a rapidly decaying turbulent field.

Sarpkaya, T., Robins, R. E. and Delisi, D. P.

"WAKE-VORTEX EDDY-DISSIPATION MODEL PREDICTIONS COMPARED WITH OBSERVATIONS"

J. Aircraft, Vol. 38, No. 4, July-August 2001, pp. 687-692.

The purpose of this paper is to describe the latest version of a wake-vortex eddy-dissipation model devised by Sarpkaya, and to compare its predictions with lidar observations obtained at Memphis and Dallas/Fort Worth airports. The model simulates the evolution of aircraft-generated trailing vortices in an atmospheric environment defined by vertical profiles of potential temperature, eddy-dissipation rate, and crosswind. Visual and quantitative comparisons of the time histories of altitude, circulation, and lateral position of such vortices are presented.

Sarrat, C., Paugam, R., Paoli, R., Cariolle, D. and Nyblen, L.

"HIGH RESOLUTION SIMULATIONS OF AIRCRAFT CONDENSATION TRAILS: CONTRAILS EVOLUTION AND DIFFUSION"

Proceedings of the 2nd International Conf. on Transport, Atmosphere and Climate (TAC-2), edited by Sausen, R., van Velthoven, P. F. J., Bruning, C. and Blum, A., June 2009, Aachen, Germany and Maastricht, The Netherlands, pp. 108-111.

This study describes a high-resolution numerical simulation of the evolution of an aircraft condensation trail (contrail) and its transition into a contrail-cirrus. The results show the extension of the contrail over 3200m width during a few hours. In particular, we show that the vertically integrated optical thickness is maintained in the core of the contrail during four hours.

Sathe, A. and Mann, J.

"A REVIEW OF TURBULENCE MEASUREMENTS USING GROUND-BASED WIND LIDARS"

Atmospheric Measurement Techniques, Vol. 6, 2013, pp. 3147-3167.

A review of turbulence measurements using ground-based wind lidars is carried out. Work performed in the last 30 yr, i.e., from 1972-2012 are analyzed. More than 80 percent of the work has been carried out in the last 15 yr, i.e., from 1997-2012. New algorithms to process the raw lidar data were pioneered in the first 15 yr, i.e., from 1972-1997, when standard techniques could not be used to measure turbulence. Obtaining unfiltered turbulence statistics from the large probe volume of the lidars has been and remains the most challenging aspect. Until now, most of the processing algorithms that have been developed have shown that by combining an isotropic turbulence model with raw lidar measurements, we can obtain unfiltered statistics. We believe that an anisotropic turbulence model will provide a more realistic measure of turbulence statistics. Future development in algorithms will depend on whether the unfiltered statistics can be obtained without the aid of any turbulence model. With the tremendous growth of the wind energy sector, we expect that lidars will be used for turbulence measurements much more than ever before.

Sathe, A. and Mann, J.

"MEASUREMENT OF TURBULENCE SPECTRA USING SCANNING PULSED WIND LIDARS"

Journal of Geophysical Research, Vol. 117, 2012, pp. D01201-1 to D01201-11.

Turbulent velocity spectra, as measured by a scanning pulsed wind lidar (WindCube), are analyzed. The relationship between ordinary velocity spectra and lidar derived spectra is mathematically very complex, and deployment of the three-dimensional spectral velocity tensor is necessary. The resulting scanning lidar spectra depend on beam angles, line-of-sight averaging, sampling rate, and the full three-dimensional structure of the turbulence being measured, in a convoluted way. The model captures the attenuation and redistribution of the spectral energy at high and low wave numbers very well. The model and measured spectra are in good agreement at two analyzed heights for the u and w components of the velocity field. An interference phenomenon is observed, both in the model and the

measurements, when the diameter of the scanning circle divided by the mean wind speed is a multiple of the time between the beam measurements. For the v spectrum, the model and the measurements agree well at both heights, except at very low wave numbers, less than 0.005/m. In this region, where the spectral tensor model has not been verified, the model overestimates the spectral energy measured by the lidar. The theoretical understanding of the shape of turbulent velocity spectra measured by scanning pulsed wind lidar is given a firm foundation.

Sathe, A., Mann, J., Gottschall, J. and Courtney, M. S.

"CAN WIND LIDARS MEASURE TURBULENCE?"

Journal of Atmospheric and Oceanic Technology, Vol. 28, July 2011, pp. 853-868.

Modeling of the systematic errors in the second-order moments of wind speeds measured by continuous-wave (ZephIR) and pulsed (WindCube) lidars is presented. These lidars use the conical scanning technique to measure the velocity field. The model captures the effect of volume illumination and conical scanning. The predictions are compared with the measurements from the ZephIR, WindCube, and sonic anemometers at a flat terrain test site under different atmospheric stability conditions. The sonic measurements are used at several heights on a meteorological mast in combination with lidars that are placed on the ground. Results show that the systematic errors are up to 90 percent for the vertical variance, whereas they are up to 70 percent for the horizontal velocity variance. For the ZephIR, the systematic errors increase with height, whereas for the WindCube, they decrease with height. The systematic errors also vary with atmospheric stability and are low for unstable conditions. In general, for both lidars, the model agrees well with the measurements at all heights and under different atmospheric stability conditions. For the ZephIR, the model results are improved when an additional low-pass filter for the 3-s scan is also modeled. It is concluded that with the current measurement configuration, these lidars cannot be used to measure turbulence precisely.

Sathe, A., Mann, J., Vasiljevic, N. and Lea, G.

"A SIX-BEAM METHOD TO MEASURE TURBULENCE STATISTICS USING GROUND-BASED WIND LIDARS"

Atmospheric Measurement Techniques, Vol. 8, 2015, pp. 729-740.

A so-called six-beam method is proposed to measure atmospheric turbulence using a ground-based wind lidar. This method requires measurement of the radial velocity variances at five equally spaced azimuth angles on the base of a scanning cone and one measurement at the center of the scanning circle, i.e. using a vertical beam at the same height. The scanning configuration is optimized to minimize the sum of the random errors in the measurement of the second-order moments of the components (u , v , w) of the wind field. We present this method as an alternative to the so-called velocity azimuth display (VAD) method that is routinely used in commercial wind lidars and which usually results in significant averaging effects of measured turbulence. In the VAD method, the high frequency radial velocity measurements are used instead of their variances. The measurements are performed using a pulsed lidar (WindScanner), and the derived turbulence statistics (using both

methods) such as the u and v variances are compared with those obtained from a reference cup anemometer and a wind vane at 89 m height under different atmospheric stabilities. The measurements show that in comparison to the reference cup anemometer, depending on the atmospheric stability and the wind field component, the six-beam method measures between 85 and 101 percent of the reference turbulence, whereas the VAD method measures between 66 and 87 percent of the reference turbulence.

Satijn, M. P., Cense, A. W., Verzicco, R., Clercx, H. J. H. and van Heijst, G. J. F.

"THREE-DIMENSIONAL STRUCTURE AND DECAY PROPERTIES OF VORTICES IN SHALLOW FLUID LAYERS"

Physics of Fluids, Vol. 13, No. 7, July 2001, pp. 1932-1945.

Recently, several laboratory experiments on vortex dynamics and quasi-two-dimensional turbulence have been performed in thin (stratified) fluid layers. Commonly, it is tacitly assumed that vertical motions, giving rise to a three-dimensional character of the flow, are inhibited by the limited vertical dimension. However, shallow water flows, which are vertically bounded by a no-slip bottom and a free surface, necessarily possess a three-dimensional structure due to the shear in the vertical direction. This shear may lead to significant secondary circulations. In this paper, the three-dimensional (3D) structure and the decay properties of vortices in shallow layers of fluid, both homogeneous and stratified, have been studied in detail by 3D direct numerical simulations. The quasi-two-dimensionality of these flows is an important issue if one is interested in a comparison of experiments of this type with purely two-dimensional theoretical models. The influence of several flow parameters, like the depth of the fluid and the Reynolds number, has been investigated. In general, it can be concluded that the flow loses its two-dimensional character for larger fluid depth and larger Reynolds number. Furthermore, it is possible to construct a regime diagram that allows the assessment of the parameter regime, where the flow can be considered as quasi-two-dimensional. It is found that the presence of secondary circulations within a planar vortex flow results in a deformation of the radial profile of axial velocity. In the limiting case of quasi-two-dimensional flow, the vorticity profiles can be scaled according to a simple diffusion model. In a two-layer stratified system, the decay is reduced and three-dimensional motions are significantly inhibited compared to the corresponding flows in a homogeneous layer.

Satran, D. R., Neuhart, D., Holbrook, G. T. and Greene, G. C.

"VORTEX RESEARCH FACILITY IMPROVEMENTS AND PRELIMINARY DENSITY STRATIFICATION EFFECTS ON VORTEX WAKES"

AIAA Paper No. 1985-0050, Reno, NV, January 1985.

The Vortex Research Facility at NASA's Langley Research Center has recently completed a facility modernization. This modernization has involved replacing the data acquisition hardware and software as well as upgrading the research vehicle. The Vortex Research Facility is a unique experimental facility in which the research model is towed the length of the facility instead of moving air past the research model as is done in conventional wind tunnels. Modern data acquisition hardware and software have

been incorporated into the facility to provide rapid acquisition of large amounts of data and efficient data reduction and presentation. The hardware improvements include a pulse coded modulation (PCM) system for acquiring model aerodynamic data and vehicle data, a change from a back-scatter to an enhanced forward-scatter laser velocimeter (LV) system for acquiring detailed wake measurements, and a minicomputer for the data acquisition and reduction for the PCM and LV systems. The improved experimental capabilities of this facility were used in a study of atmospheric stratification effects on wake vortex decay. Density stratification was produced by a test section temperature gradient resulting in a significant effect on the decay of the wake vortex system. The stratification results indicate that temperature gradient effects must be considered to avoid misleading conclusions in wake vortex research.

Satti, R., Li, Y., Shock, R. and Duncan, B.

"COMPUTATIONAL ANALYSIS OF A WINGTIP VORTEX IN THE NEAR-FIELD USING LBM-VLES APPROACH, AIAA Paper No. 2011-0679"

In recent years, the near-field flow behavior of the tip vortex originating from airfoils has been widely studied to provide insight into the complex physics governing the growth and propagation of wingtip vortices. For this purpose, extensive experiments on a semi-span NACA0012 airfoil were recently conducted in the low-speed wind tunnel at NASA Ames Research Center to provide data for benchmarking CFD codes. In the current study, a Lattice Boltzmann Method based very large eddy simulation (LBM-VLES) approach was used to simulate flow past a semi-span NACA0012 airfoil with rounded wingtip. Time-dependent, three-dimensional simulations were conducted to compute the span wise distribution of mean pressure coefficient and the mean velocity field distributions around the tip vortex region. The computed results for the mean flow field, including surface pressure distribution, flow field velocity through the vortex core, and the location of the vortex core were found to agree well with experimental data. Further, an in-depth analysis of the unsteady flow field and the comparison and validation of computational results for the Reynolds stress tensor is planned for future work.

Sau, R. and Mahesh, K.

"DYNAMICS AND MIXING OF VORTEX RINGS IN CROSSFLOW"

Journal of Fluid Mechanics, Vol. 604, 2008, pp. 389-409.

Direct numerical simulation is used to study the effect of crossflow on the dynamics, entrainment and mixing characteristics of vortex rings issuing from a circular nozzle. Three distinct regimes exist, depending on the velocity ratio (ratio of the average nozzle exit velocity to free-stream crossflow velocity) and stroke ratio (ratio of stroke length to nozzle exit diameter). Coherent vortex rings are not obtained at velocity ratios below approximately 2. At these low velocity ratios, the vorticity in the crossflow boundary layer inhibits roll-up of the nozzle boundary layer at the leading edge. As a result, a hairpin vortex forms instead of a vortex ring. For large stroke ratios and velocity ratio below 2, a series of hairpin vortices is shed downstream. The shedding is quite periodic for very low Reynolds numbers. For velocity ratios above 2, two regimes are obtained depending upon the stroke ratio. Lower stroke

ratios yield a coherent asymmetric vortex ring, while higher stroke ratios yield an asymmetric vortex ring accompanied by a trailing column of vorticity. These two regimes are separated by a transition stroke ratio whose value decreases with decreasing velocity ratio. For very high values of the velocity ratio, the transition stroke ratio approaches the 'formation number'. In the absence of trailing vorticity, the vortex ring tilts towards the upstream direction, while the presence of a trailing column causes it to tilt downstream. This behavior is explained. In the absence of crossflow, the trailing column is not very effective at entrainment, and is best avoided for optimal mixing and entrainment. However, in the presence of crossflow, the trailing column is found to contribute significantly to the overall mixing and entrainment. The trailing column interacts with the crossflow to generate a region of high pressure downstream of the nozzle that drives crossflow fluid towards the vortex ring. There is an optimal length of the trailing column for maximum downstream entrainment. A classification map which categorizes the different regimes is developed.

Sau, R. and Mahesh, K.

"PASSIVE SCALAR MIXING IN VORTEX RINGS"

J. Fluid Mech., Vol. 582, 2007, pp. 449-461

Direct numerical simulation is used to study the mixing of a passive scalar by a vortex ring issuing from a nozzle into stationary fluid. The 'formation number' (Gharib et al. J. Fluid Mech. Vol. 360, 1998, p. 121), is found to be 3.6. Simulations are performed for a range of stroke ratios (ratio of stroke length to nozzle exit diameter) encompassing the formation number, and the effect of stroke ratio on entrainment and mixing is examined. When the stroke ratio is greater than the formation number, the resulting vortex ring with trailing column of fluid is shown to be less effective at mixing and entrainment. As the ring forms, ambient fluid is entrained radially into the ring from the region outside the nozzle exit. This entrainment stops once the ring forms, and is absent in the trailing column. The rate of change of scalar-containing fluid is found to depend linearly on stroke ratio until the formation number is reached, and falls below the linear curve for stroke ratios greater than the formation number. This behavior is explained by considering the entrainment to be a combination of that due to the leading vortex ring and that due to the trailing column. For stroke ratios less than the formation number, the trailing column is absent, and the size of the vortex ring increases with stroke ratio, resulting in increased mixing. For stroke ratios above the formation number, the leading vortex ring remains the same, and the length of the trailing column increases with stroke ratio. The overall entrainment decreases as a result.

Sau, R. and Mahesh, K.

"THE EFFECT OF CROSSFLOW ON VORTEX RINGS"

AIAA Paper No. 2007-1316, Reno, NV, January 2007

DNS is performed to study passive scalar mixing in vortex rings in the presence, and absence of crossflow. For vortex rings without crossflow, the 'formation number' (Gharib et. al 1998) is found to be

3.6. Simulations are performed for a range of stroke ratios encompassing the formation number. In the absence of crossflow, the optimal stroke ratio for mixing and entrainment is shown to be at the formation number; the trailing column is not seen to be as beneficial as the ring itself. However, in the presence of crossflow, the trailing column is shown to contribute significantly because of the high-pressure gradient created by deformation of the column upon interacting with crossflow. It is shown that the crossflow reduces the stroke ratio beyond which the trailing column forms. This reduction in stroke ratio is due to entrainment of crossflow fluid during formation of the ring, and depends on the velocity ratio.

Saudreau, M. and Moet, H.

"CHARACTERIZATION OF EXTENDED NEAR-FIELD AND CROW INSTABILITY IN THE FAR-FIELD OF A REALISTIC AIRCRAFT WAKE"

European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS 2004, Jyväskylä, Finland, July 2004

Experimental data is used to generate the initial condition for a computation that predicts the wake evolution from the near-field to extended near-field. The Large-Eddy Simulation approach was followed to simulate the roll-up of the vorticity sheet and the subsequent merging of the primary co-rotating vortices. It leads to the formation of a wake that is primarily composed of a counter-rotating vortex pair. The final vortex structure appears to be best described by at least a two-scale velocity profile. A simulation of a generic configuration composed of a counter-rotating vortex pair was carried out to investigate the Crow instability in the far-field. For this purpose, the generic configuration is generated using the characteristics of the vortex structure that is recovered at the end of the extended near-field simulation. The results have shown that the natural development of the Crow instability is insufficient to reduce the strength of the realistic aircraft wake considered in this study at approximately 100 spans behind the aircraft.

Saunier, O., Peron, S., Jeanfaivre, G., Benoit, C. and Lerat, A.

"HIGH-ORDER ACCURATE CARTESIAN PARTITIONING METHODS. APPLICATION TO ROTOR FLOWS"

TP-2007-147, September 2007, 33rd European Rotorcraft Forum - ERF 2007, Kazan, Russia

In the present article, a coupling between the mesh adaptation technique of Meaking and high-order numerical schemes is proposed. Several schemes for introducing an artificial dissipation into a high-order central finite volume approximation to the Euler equations are considered. Transfers in overlap regions are completed by high-order interpolations. The methods applied to the computation of 2D parallel blade-vortex interaction and to the simulation of a 3D flow around a hovering blade of the ONERA 7A helicopter rotor exhibiting an improvement in the wake capture.

Sauvage, L., Isambert, E., Winckelmans, G., Cariou, J. P. and Dolfi, A.

"PREPARATION OF WAKE VORTEX DETECTION TECHNOLOGY CASE"

EEC/TRS-C52, March 2005, Eurocontrol, France

The objective of the Eurocontrol project WAKESEP is to propose extensions to the current ICAO separations with a set of separations based on an understanding of wake vortex behavior under different atmospheric conditions. For ATC operations, four critical areas with respect to Wake Vortex (WV) encounter risk (2 areas for arrivals, 2 areas for departures) have been defined.

Savas, O.

"EXPERIMENTAL INVESTIGATIONS ON WAKE VORTICES AND THEIR ALLEVIATION"

C. R. Physique, Vol. 6, 2005, pp. 415-429

Recent wake vortex research in the laboratory has benefited considerably from concurrent analytical and numerical research on the instability of vortex systems. Tow tank, with dye flow visualization and particle image velocimetry is the most effective combination for laboratory research. Passive and active wake alleviation schemes have been successfully demonstrated in the laboratory. The passive alleviation systems exploit the natural evolution of vortex instabilities while the active systems rely on hastening selected instabilities by forcing the vortices individually or as a system. Their practical applicability, however, will have to meet further criteria beyond those dictated by fluid dynamics.

Savas, O.

"EXPERIMENTAL STUDY OF COMPLEX VORTEX INTERACTIONS IN THE WAKE OF HIGH ASPECT RATIO WINGS"

NASA/CR-112556, August 1997, Univ. of California, Berkeley, CA

The dynamics of trailing vortex wakes from flapped airfoils are investigated in a towing tank and a wind tunnel. In this work, parallel experiments are conducted in a wind tunnel with a five-hole probe for near wake measurements and in a tow tank with particle image velocimetry for mid- and far-wake measurements. The wind tunnel allows detailed time-averaged measurements of the near-wake in a plane fixed relative to the wing while the tow tank allows measurements of the entire evolving wake in a plane fixed relative to an observer. The wakes from a lifting rectangular circular arc airfoil with an aspect ratio of 6 and flap-spans of 30% and 67% and a NACA 0012 with an aspect ratio of 8 and flap-spans of 40% and 50% are studied as the wake evolves downstream. Chord-based Reynolds number $Re(\text{sub } c)$, ranged from 15000 to 80000. A traversing five-hole pitot probe and Lagrangian Parcel Tracking are used to measure the velocity field in a cross-stream plane behind the wing in the wind tunnel and the towing tank, respectively. The interaction of the tip and flap vortices are studied. Merger of the flap and tip vortices usually occurs within one orbit, leading to a shorter descent distance to merger for the longer flap-spans. The strut wake significantly affects the vortex strength, hence merger characteristics, by disrupting the vortex sheet.

Savas, O., Green, R. B. and Caradonna, F. X.

"COUPLED THRUST AND VORTICITY DYNAMICS DURING VRS"

American Helicopter Society Specialists' Conf. on Aeromechanics, Jan. 2008, San Francisco, CA.

The focus is on the vortex ring state (VRS) observed at rapid descent rates. At VRS, the helical vortex filaments coming off the blades amalgamate around the rotor disk forming a vortex ring, which periodically detaches into the wake, causing extreme oscillations in thrust, with periods on the order of several tens of rotor revolutions. We discuss here the phase relation between the thrust cycle and vorticity distribution at the rotor disk. Maxima of the VRS thrust oscillations correlate well with the maxima of circulation, enstrophy, and minima of enstrophy dispersion radius observed in the vicinity of the rotor disk.

Savas, O., Ortega, J. M. and Bristol, R. L.

"WAKE ALLEVIATION THROUGH CONTROL VORTEX INSTABILITIES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

A series of experiments are carried out in the vortex wakes of wings with outboard flaps, which are used to generate control vortices. A rapidly growing instability is observed to develop between unequal strength, counter-rotating vortex pairs in the wakes of airfoils with outboard triangular flaps. Unlike the wake of a simple rectangular airfoil, the wakes of the triangular-flapped airfoils become highly unsteady and complex as the result of this instability. The qualitative features of the instability, such as its wavelength and non-linear evolution, are examined by flow visualization measurements that are made in a towing tank at a chord-based Reynolds number of 100,000. This sinuous instability is seen to develop on the weaker flap vortices and have a wavelength of order one wingspan. Typically, the instability requires about 15 wingspans to become finite in amplitude. Planar velocity field measurements of the vortex wakes are made with a PIV technique, allowing the vortex structure, trajectories, kinetic energy, and distribution to be assessed up to several hundred wingspans downstream of the airfoils. For angles of attack ranging from -1.0 to 2.0 degrees, the circulation strength ratio of the flap and tip vortices ranges from -0.7 to -0.4. Additionally, the circulation-based Reynolds number is seen to be of order 100,000. The PIV data indicate that the wake's two-dimensional kinetic energy decreases substantially as the instability transforms the two-dimensional nature of the wake into a three-dimensional one. The wake alleviation properties of these wings are estimated using the PIV data, following Rossow (1976). The non-linear interactions between the vortices result in a wake that is highly three-dimensional and incoherent. These effects are reflected in large decreases in both the rolling moment and downwash on a simulated following wing. The results are compared to those of a rectangular wing. For all the experimental runs, the wakes of the triangular-flapped wings have a maximum rolling moment and downwash that are substantially less than those of the rectangular wing. In particular, non-dimensional rolling moment and downwash are about 1/3 of those of a comparable rectangular wing. The results of this study indicate that the triangular-flapped wing design offers a possible solution to the wake hazard problem.

Sayers, W. H.

"VORTICISM IN AERONAUTICS"

NACA TM-222, August 1923, NACA Langley Aero. Lab., Langley Field, VA

Since the war there has been a considerable advance in knowledge about the airfoil and its behavior. The theory is now sufficiently advanced to make it possible to predict and to calculate certain results which previously could only be attained by direct experiment. The vortex theory receives special attention.

Scarano, F., van Wijk, C. and Veldhuis, L. L. M.

"TRAVERSING FIELD OF VIEW AND AR-PIV FOR MID-FIELD WAKE VORTEX INVESTIGATION IN A TOWING TANK"

Experiments in Fluids, Vol. 33, 2002, pp. 950-961.

Wake vortex flow experiments are performed in a water tank where a 1:48 scaled model of a large transport aircraft A340-300 is towed at a speed of 3 and 5 m/s with several values of the angle of attack (2, 4, 8 degrees). Particle image velocimetry (PIV) measurements are performed in a plane perpendicular to the towing direction describing the streamwise component of the wake vorticity. The instantaneous field of view (I-FOV) is traversed vertically with an underwater moving-camera device tracking the vortex core during the downward motion. An adaptive resolution (AR) image-processing technique is introduced that enhances the PIV interrogation in terms of spatial resolution and accuracy. The main objectives of the investigation are to demonstrate the applicability of PIV diagnostics in wake vortex research with towing-tank facilities. The specific implementation of the traversing field-of-view (T-FOV) technique and the AR image processing are driven by the need to characterize the vortex wake global properties as well as the vortex decay phenomenon in the mid- and far-field. Relevant aerodynamic information is obtained in the mid-field where the time evolution of the vortex structure (core radius and tangential velocity) and of the overall vortex wake (vortex trajectory, descent velocity, circulation) are discussed.

Scarano, F., van Wijk, C. and Veldhuis, L. L. M.

"TRAVERSING FIELD-OF-VIEW AND AR-PIV FOR MID FIELD WAKE VORTEX INVESTIGATION IN A TOWING TANK"

4th International Symposium on Particle Image Velocimetry, Gottingen, Germany, September 2001.

Wake vortex flow experiments are performed in a water tank where a 1/48 scaled model of an Airbus A340-300 is towed at a speed of 3 and 5 m/s with several values of the angle of attack (2, 4, 8 degrees). PIV measurements are obtained in a fixed plane perpendicular to the towing direction to measure the streamwise component of the wake vorticity. An underwater moving camera device is used to keep the

moving vortex in the field of view during the vortex whole downward motion. An adaptive resolution (AR) image processing technique is employed to further enhance the technique capability in terms of spatial resolution and accuracy. An extensive measurement campaign yields the wake vortex behavior described during a period that extends from the vortex formation stage up to the mid-field (200 wingspans). Results show a constant vortex downward motion up to about 100 wingspans. Further, the vortex wake interaction with the bottom wall constitutes the main limitation to the investigation of vortex decay phenomena in the far-field. The analysis of the vortex structure yields important insights on the time evolution of the vortex velocity distribution. The maximum tangential velocity, the peak vorticity and the vortex core radius are the main parameters addressed in the discussion of the time evolution of the wake vortex properties.

Scase, M. M. and Dalziel, S. B.

"AN EXPERIMENTAL STUDY OF THE BULK PROPERTIES OF VORTEX RINGS TRANSLATING THROUGH A STRATIFIED FLUID"

European Journal of Mechanics, B/Fluids, Vol. 25, 2006, pp. 302-320

Experiments are carried out to find the bulk properties and some structural properties of vortex rings in a stratified fluid. Previous theoretical descriptions of vortex ring propagation speed in a homogeneous fluid are compared to experiment and developed for use in stratified fluids. Vortex rings are fired at oblique angles to the horizontal and at different speeds through a stratified fluid. The buoyancy frequency of the fluid is varied between different series of experiments. New models are proposed which predict the speeds and trajectories of vortex rings fired through a stratified fluid and these are compared to experiment. It is shown that these models perform well in high Froude number flows, but less well in low Froude number flows.

Schaeffer, N. and Le Dizes, S.

"NONLINEAR DYNAMICS OF THE SHORT-WAVELENGTH ELLIPTIC INSTABILITY"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

The nonlinear dynamics of the elliptic instability has been studied by Direct Numerical Simulation with a pseudo-spectral code. As the main objective was to analyze the effect of the axial flow, we have first performed a series of simulations to better characterize the nonlinear dynamics of the elliptic instability without axial flow. We have considered the configurations of a single strained Lamb-Oseen vortex and of a system of two counter-rotating Lamb-Oseen vortices. For both cases, we have demonstrated that both weakly nonlinear and strongly nonlinear evolution of the elliptic instability were possible. The weakly nonlinear dynamics which has been observed very close to threshold is characterized by a limit cycle behavior. The strongly nonlinear dynamics, which has been obtained in most simulations, is much more violent but possesses some universal characteristic features. We have shown that it always follows the following steps: (1) concentration of the vorticity in thin layers at the

periphery of the vortex, (2) expulsion of vortex loops, (3) breakdown of the whole structure, (4) laminarization process leading to the reformation of a weaker and larger vortex. The instability can start again and the process can repeat several times leading to larger and larger vortices.

Schaffer, A.

"A STUDY OF VORTEX CANCELLATION"

Journal of Aerospace Sciences, Vol. 27, No. 3, 1960, pp96.

The cancellation of a vortex by means of another concentric vortex of equal strength but opposite spin is investigated. When such a cancellation occurs, there is a recovery of static pressure. The vortices are generated by means of two three-dimensional airfoils cantilevered from the duct wall, one being situated in the wake of the other. The airfoils have opposite effective angles of attack and therefore have trailing vortices of opposite spin, as required. It is documented experimentally that there exists an optimum angle of attack for the second airfoil which cancels the vortex from the first airfoil and restores uniform flow downstream of the two airfoils. A theoretical solution of this optimum angle of attack is presented, and it is found to depend upon the angle of attack of the first airfoil and upon the geometrical properties of the wings. The pressure recovery accompanying the vortex cancellation is also studied. Theoretical considerations, based on the model of a vortex filament in the center of a circular tube show that a maximum of 62 per cent of the static pressure drop across the first airfoil can be recovered. This maximum is imposed, irrespective of skin friction and separation losses, by the irreversibility associated with establishing a vortex field. Experimental pressure recoveries of 50 per cent are realized.

Schauerhamer, D. G. and Robinson, S. K.

"SIMULATING AIRCRAFT WAKE VORTICES WITH OVERFLOW"

AIAA Paper 2015-3301, June 2015, Dallas, TX.

Low dissipation methods were used to simulate wake vortex generation using the OVERFLOW computational fluid dynamics solver. The study involved varying parameters such as grid spacing, time step, high order spatial and temporal methods, turbulence modeling, and automatic grid adaption. A two-dimensional inviscid vortex was analyzed to assess numerical dissipation, then the practices learned were applied to a finite wing and a full aircraft. Comparisons were made to idealized vortex models, the finite wing compared closest to the Hallock-Burnham model and the full aircraft to the Proctor model.

Schauerhamer, D. G. and Robinson, S. K.

"A VALIDATION STUDY OF OVERFLOW FOR WING-TIP VORTICES"

AIAA Paper 2016-1782, January 2016, San Diego, CA.

A validation study of the computational fluid dynamics flow solver OVERFLOW simulating wing-tip vortices was conducted using data from two wind tunnel tests. The first test was of a semi-span wing conducted in the NASA Ames Research Center Fluid Mechanics Laboratory, and included surface pressure measurements and measurements of the trailing vortex using a pressure probe. Best practices of the OVERFLOW solver were established through grid and time step sensitivity studies and comparing to test data. Methods include high-order accurate spatial methods and detached eddy simulation turbulence modeling. The best practices from the first test were applied to a second wind tunnel test of a generic wing/body aircraft with slat and flap extended. For both tests, comparisons with test data and with algebraic vortex models are presented and sources of uncertainties and any deviations are discussed.

Schauerhamer, D. G. and Robinson, S. K.

"TOWARDS SIMULATING THE EVOLUTION OF AIRCRAFT WAKE VORTICES WITH OVERFLOW"

AIAA Paper 2017-0956, January 2017, Grapevine, TX.

Best practices towards simulating the evolution of aircraft wake vortices were developed with a systematic approach using two-dimensional simulations. The simulations were initialized with either idealized vortex models or a simulated wake system produced by the NASA Common Research Model. Simulations evolved the vortex system to over 8 times the wing span downstream from the wing trailing edge. Sensitivity studies were completed to establish time accurate methods and convergence, as well as the use of automatic mesh refinement. Errors involved in using symmetry boundary conditions and running on a different number of processors were also addressed. The resulting evolved wake vortices were compared to idealized vortex models.

Schauerhamer, D. G. and Robinson, S. K.

"AIRCRAFT EFFECTS IN WAKE VORTEX DECAY SIMULATIONS"

AIAA Paper 2017-3035, June 2017, Denver, CO.

Aircraft wake vortex decay simulations were carried out that included aircraft effects. Low dissipation Reynolds Averaged Navier-Stokes Computational Fluid Dynamics were used to generate wing tip vortices from the NASA Common Research Model with and without a generic winglet. The wake was propagated with two-dimensional evolution and coarse-mesh three-dimensional simulations. Vortex decay simulations were initialized with results from the aircraft simulations and compared to decay simulations initialized with idealized vortex models. Some numerical artifacts existed in the decay simulations. Comparisons between decay simulations with aircraft effects and decay simulations initialized with idealized vortex models had differences in vortex position, descent rate, and circulation..

Schauerhamer, D. G. and Robinson, S. K.

"COMPUTATIONAL-FLUID-DYNAMICS BEST PRACTICES FOR AIRCRAFT WING-TIP VORTEX ROLL-UP"

Journal of Aircraft, Vol. 54, No. 4, July-August 2017, pp. 1552-1565.

Best practices for simulating aircraft wing-tip vortex roll-up with Reynolds-averaged Navier-Stokes computational fluid dynamics were developed using a build-up approach with the NASA OVERFLOW flow solver. Methods were tested for accuracy and computational expense beginning with a simple case, then building up step by step in complexity toward a realistic aircraft geometry. The cases tested were started two-dimensionally with an inviscid vortex, then a viscous vortex, then three-dimensionally with a basic rectangular finite wing, a semispan wing that included validating wind-tunnel test data, and finally to a realistic wing/body aircraft configuration that also included wind-tunnel data. Comparisons were also made with algebraic vortex models used to initialize large-eddy simulations of wake decay.

Schauerhamer, D. G. and Robinson, S. K.

"SENSITIVITY STUDY OF AIRCRAFT WAKE VORTICES USING OVERFLOW"

AIAA Paper 2016-3137, June 2016, Washington, DC.

A sensitivity study on aircraft wing tip vortices was conducted with low dissipation computational fluid dynamics. Using the OVERFLOW flow solver, simulations of full aircraft were conducted. An aircraft in high lift configuration with slat and flap extended was used, and the effect of varying degrees of geometric fidelity was tested. Also, a cruise configuration aircraft was used with and without a generic winglet. Validation of the simulations was conducted with data from wind tunnel tests. The wake vortices were sensitive to the aircraft state. Of the aircraft in this study, the aircraft with the slat and flap extended with the lowest geometric fidelity produced the strongest vortex, and the cruise configuration with the generic winglet produced the weakest. Comparisons were made with algebraic vortex models used to initialize Large Eddy Simulations. No model accurately portrayed the vortices from the OVERFLOW simulations, but for the aircraft and conditions tested, the Proctor model was the closest.

Scheiman, J. and Shivers, J. P.

"EXPLORATORY INVESTIGATION OF THE STRUCTURE OF THE TIP VORTEX OF A SEMISPAN WING FOR SEVERAL WING-TIP MODIFICATIONS"

NASA TN D-6101, February 1971, NASA Langley Research Center, Hampton, VA

Wind-tunnel tests were performed on a semispan wing with rather radical wing-tip modifications. These modifications were chosen in an attempt to deform, displace, or modify the cross-sectional characteristics of the trailing tip vortex. The wing-tip modifications test did not grossly affect the spanwise lift distribution and did not produce a noticeable change in the position of the downstream tip vortex. Tip-vortex cross-sectional variations were obtained such that the outer flow field was no longer potential flow.

Scheiman, J., Shivers, J. P. and Megrail, J. L.

"EXPLORATORY INVESTIGATION OF FACTORS AFFECTING THE WING TIP VORTEX"

NASA TM X-2516, April 1972, NASA Langley Research Center, Hampton, VA

An investigation was conducted in the Langley full-scale tunnel to study some factors affecting the tip vortex of a wing. It was found that there was a pronounced effect of Reynolds number on the tip-vortex core size. An attempt was made to determine what aerodynamic parameters - such as lift, drag, or induced drag - influence the size of the vortex core, but no function of the parameters was found to be superior to all others. Various spoilers placed on the upper and lower surfaces of the wing to increase the boundary-layer thickness resulted in a reduction in the vorticity as determined from the tuft grid. Various solid objects placed in the vortex core downstream of the wing tip seemed to decrease the vorticity within the vortex core.

Schell, I., Ozger, E. and Jacob, D.

"INFLUENCE OF DIFFERENT FLAP SETTINGS ON THE HAZARD POSED TO FOLLOWING AIRCRAFT"

In New Results in Numerical and Experimental Fluid Mechanics III, Notes on Numerical Fluid Mechanics, Vol. 77, Eds. Wagner, et al., Springer-Verlag, Berlin Heidelberg, 2002, pp. 66-73.

In the present paper the influence of different flap settings of the wake generating aircraft on the hazard posed to a following aircraft is investigated. The near wake region of a rectangular wing with flaps is computed by means of a 3D panel method while the far wake region is simulated by a 2D Navier Stokes scheme in vorticity form. The hazard posed to a following aircraft is quantified by the value of the maximum induced rolling moment which is calculated by means of 2D strip theory. A preceding experimental investigation showed that the maximum induced rolling moment on the following aircraft related to the wing lift of the generating aircraft is decreased by deflecting the flaps. This result is confirmed by the numerical simulation for moderate flap deflections whereas higher flap angles lead to an increase of the maximum induced rolling moment related to the wing lift. The computation of the far wake region shows that in these cases the merger of the wing tip and flap vortex leads to a reconcentration of circulation and a reduction of the alleviating effect of the flap deflection.

Schell, I., Ozger, E. and Jacob, D.

"INFLUENCE OF DIFFERENT FLAP SETTINGS ON THE WAKE-VORTEX STRUCTURE OF A RECTANGULAR WING WITH FLAPS AND MEANS OF ALLEVIATION WITH WING FINS"

Aerospace Science and Technology, Vol. 4, No. 2, February 2000, pp. 79-90

This paper presents the results of an experimental investigation of the wake-vortex structure behind a flapped rectangular wing. The wind-tunnel test is to investigate the flow structure in the wake of wings with different flap extensions. The purpose of this investigation is to study the main features of lift generated vortices to find ways to alleviate hazardous wake vortex encounters for following airplanes during start and approach such that an increase in airport capacity can be achieved. First, the wake

structure at different flap settings is investigated by measuring the velocity field at different positions in the near field behind the wing. The measured data are evaluated in terms of vortex parameters such as core radius, maximum tangential velocities, circulation distributions, turbulence levels and maximum induced rolling moments on a following aircraft. Then additionally, for one flap setting, means of alleviation are examined with a wing fin mounted at different positions on the wing. Alleviation is judged by the decrease of the maximum induced rolling moment. A significant reduction is achieved for a wing fin placed near the outboard edge of the flap.

Schiavetta, L. A., Boelens, O. J., Crippa, S., Cummings, R. M., Fritz, W. and Babcock, K. J.

"SHOCK EFFECTS ON DELTA WING VORTEX BREAKDOWN"

Journal of Aircraft, Vol. 46, No. 3, May-June 2009, pp. 903-914.

It has been observed that delta wings placed in a transonic freestream can experience a sudden movement of the vortex breakdown location as the angle of incidence is increased. The current paper uses computational fluid dynamics to examine this behavior in detail. The study shows that a shock/vortex interaction is responsible. The balance of the vortex strength and axial flow and the shock strength are examined to provide an explanation of the sensitivity of the breakdown location. Limited experimental data are available to supplement the computational fluid dynamics results in certain key respects, and the ideal synergy between computational fluid dynamics and experiments for this problem is considered.

Schick, F. V. and Reichmuth, J.

"EVALUATION OF OPERATIONAL CONCEPTS OF A WAKE VORTEX WARNING SYSTEM"

Z. Flugwiss. Weltraumforsch., Vol. 18, 1994, pp. 54-59

In an Air Traffic Control (ATC) simulation study with 15 ATC controllers as subjects, three different operational concepts of utilizing a Wake Vortex Warning System (WVWS) were investigated. Traffic flow data, operational data and controller judgments which were obtained from real-time simulations were analyzed, and discussed in terms of operational performance, controller workload and controller acceptance of the concepts tested. In the simulation environment, an increase of landing capacity was realizable. Based on detailed findings specific for the various concepts, some conclusions were drawn, regarding display layout and operational procedures of a future advanced WVWS concept. [In German.]

Schilling, V.

"MOTION AND DECAY OF TRAILING VORTICES WITHIN THE ATMOSPHERIC SURFACE LAYER"

Beitr. Phys. Atmosph., Vol. 65, No. 2, May 1992, pp. 157-169

Results of investigations of aircraft induced trailing vortices within the atmospheric surface layer (ASL) are presented. Using a two-dimensional numerical model, the influence of stratification and wind shear on the motion, structure and decay of those vortices has been studied. It is depicted, for example, that the shifting of vortex wakes is weakly influenced by the thermal stratification of the atmosphere (in accordance with measurements of Franke, Kopp & Tetzlaff (1991) (FKT '91)), while the background wind and wind shear are found to be more important factors. Special attention is directed to formation and influence of secondary vortices. An attempt is made to describe, in which way they are responsible for the observed 'rebounding' of the primary vortices. It is found, that the development of this phenomenon depends strongly on the background crosswind and may also occur in the absence of any wind shear within the ASL. Without doubt, these secondary vortices are responsible for a possible spiral path of the vortex trajectories. These phenomena have to be taken into consideration (as an important factor), when problems of landing and take-off frequencies of different aircraft will be studied. Comparisons of the computed results with the measurements of FKT '91 at the Frankfurt International Airport (FIA) show corresponding movement and a maximum lifetime (3 min.) of the trailing vortices as well as the same critical crosswind velocity ($U_{min} = 2.5 \text{ m/s}$), which is necessary to transport vortices to a parallel runway at the FIA.

Schilling, V. and Etling, D.

"DISPERSION OF AIRCRAFT EMISSIONS DUE TO WAKE VORTICES"

In: Impact of Emissions from Aircraft and Spacecraft Upon the Atmosphere, Proceedings of International Scientific Colloquium, Cologne, Germany, 1992, pp. 315-320

The development of the wake vortex system behind a B-747 airplane and the dispersion of the aircraft emissions due to these vortices have been studied numerically by using a 2D model including a dynamic (Eulerian) and a dispersion (Lagrangian) part. Representing one of the simulation experiments, we demonstrate the influence of a strong temperature inversion on the development of the vortex-emission system. We found the lifetime of the wake vortices limited to about one minute, and the dispersion efficiency of the whole process is quantified by a scale dependent vertical diffusion coefficient.

Schilling, V., Siano, S. and Etling, D.

"DISPERSION OF AIRCRAFT EMISSIONS DUE TO WAKE VORTICES IN STRATIFIED SHEAR FLOWS: A TWO-DIMENSIONAL NUMERICAL STUDY"

J. Geophysical Research, Vol. 101, No. D15, September 1996, pp. 20965-20974

The development of the wake vortex system behind an airplane (B-747) at cruising altitude (8-15 km) and the dispersion of the aircraft emissions due to this vortex system have been studied by means of a two-dimensional numerical model. Simulation experiments are presented which examine the influence of atmospheric stratification and vertical wind shear on the combined vortex-emission system. Although the development of the vortex wake system can be influenced by three-dimensional effects

(e.g., Crow instabilities), the undisturbed process can be approximated as a two-dimensional phenomenon, which allows the study of details of the vortex structures at small scales (length L about 1 m) and the dispersion of engine exhausts at larger scales (L about 100 m). The results of simulation experiments show that the maximum lifetime of the wake vortices (120 s to 300 s) as well as the descending rate (1.2 m/s to 2.4 m/s) and the dispersion of the emitted substances depend on the atmospheric stratification as well as vertical wind shear, but buoyancy forces seem to dominate over shear forces. The overall dispersion of aircraft emissions due to the wake vortex system can be quantified by a vertical standard deviation for the entire process of less than or equal to 70 m.

Schillings, J. J., Ferguson, S. W., Brand, A. G., Mullins, B. R. and Libby, J.

"WAKE VORTEX MEASUREMENTS OF THE XV-15 TILTROTOR USING A MOBILE GROUND-BASED LIDAR SYSTEM"

57th Annual Forum, American Helicopter Society, May 2001, Washington, DC.

The paper presents initial results of a research program to measure trailing wake vortices of tiltrotor aircraft. Wake measurements of the Bell XV-15 were made using the MIT Lincoln Laboratory Lidar system. Measured data include time histories of vortex positions, circulation strengths, and wake velocities. Selected data from each of the XV-15's modes of flight are included in the paper. In airplane mode, the trailing wake resembles the wake of a fixed-wing aircraft of equal weight. In helicopter mode, the wake consists of a pair of vortices separated by the distance between the advancing blade tips. In conversion mode, the separation distance of the vortices is approximately a linear function of nacelle angle. Initial circulation is calculated using an analytical method and compared to flight test. This analytical method suggests that during helicopter and conversion mode flight the wing tip vortex combines with the vortex from the advancing blades, while the vorticity from the retreating blades has a weaker influence.

Schlink, U. and Tetzlaff, G.

"WIND SPEED FORECASTING FROM 1 TO 30 MINUTES"

Theoretical and Applied Climatology, Vol. 60, 1998, pp. 191-198

The long lifetime and high intensity of vortex trails generated by landing large-capacity aircraft may cause a risk to subsequently landing planes. A wake vortex warning system can help to avoid such hazards by forecasting the time intervals permitting safe operation on the landing strip. This information provides the basis for an appropriate landing schedule based on reduced succession distances. An essential element of the warning system is the prediction of wind across the landing strip and this is commonly determined by a method based on the principle of persistence. This study shows that autoregressive (AR) modelling can improve the accuracy of crosswind forecasts. To this end, the measurements are analyzed to estimate model parameters. Unlike the more simplistic previously used method, AR forecasting, as part of the vortex trail warning system, allows longer intervals for safe

operation and can avoid forecast discontinuities (leaps) which are inherent problems of all forecasts in which boundary layer processes must be considered.

Schmid, P. J. and Rossi, M.

"THREE-DIMENSIONAL STABILITY OF A BURGERS VORTEX"

J. Fluid Mech., Vol. 500, 2004, pp. 103-112

The evolution of infinitesimal three-dimensional perturbations superimposed on a Burgers vortex is studied. By a sequence of variable transformations and scalings this linear evolution problem is reduced to a time-dependent system which is nearly identical to the stability equations governing a Lamb-Oseen vortex. The maximum amplification reached by perturbations over a finite time interval is computed through an iterative scheme based on the direct and adjoint governing equations, and results on the asymptotic stability of the Burgers vortex are deduced. The Burgers vortex is shown to be asymptotically stable, although significant short-term amplification may occur.

Schmidt, L. V. and Duren, R. W.

"WING INDUCED DRAG"

AIAA Paper No. 2002-4878, Monterey, CA, August 2002

The purpose of this study is to show that modern computational power using an elementary lifting surface theory is in accord with the oft-quoted statement that the minimum induced drag due to angle of attack on a wing occurs when the wing span load distribution is elliptical. However, the caveat must be introduced that the classical studies applied to a wing with an unswept quarter chord line. It will subsequently be shown by analyzing a straight-tapered wing with an 0.40 taper ratio that wing sweep angle has a significant effect upon the wing's induced drag.

Schmitt, N. P., Rehm, W., Pistner, Th., Diehl, H., Nave, P. and Rabadan, G. J.

"A340 FLIGHT TEST RESULTS OF A DIRECT DETECTION ONBOARD UV LIDAR IN FORWARD-LOOKING TURBULENCE MEASUREMENT CONFIGURATION"

Proceedings of the 15th Coherent Laser Radar Conference, June 2009, Toulouse, France, pp. 169-172.

A direct detection short pulse UV Doppler LIDAR onboard aircraft sensor for forward looking air speed / turbulence measurement was developed and flight tested. This detection schemes allows measurements even in aerosol-depleted air at distances of 50 m, which is necessary for reliable and high-frequency measurements of clear air turbulence at cruise altitude. A fringe-imaging technique was used applying an intensified CCD camera, allowing fast gating for longitudinal measure volume reduction (as necessary for real-time control purposes) and in-flight re-calibration by image processing. Algorithms have been developed and applied to determine the wind speed around 1 m/s accuracy. The forward measured air speed / turbulence data shall later be directly fed forward into the flight control

of an aircraft. The paper describes the results achieved in flight tests using an Airbus A340-300 aircraft used as test-bed with the forward-looking direct detection LIDAR to measure turbulences ahead, which was integrated in a fairing below the aircraft nose.

Schmitz, M. and Klein, R.

"RECENT DEVELOPMENT IN THE ASYMPTOTIC THEORY OF VORTEX BREAKDOWN"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

This lecture will summarize the generalized asymptotic theory involving axial core structure variations on a three-dimensional slender vortex filament. It will describe in some detail the critical layer theory. Results include a comparison with direct numerical simulations done at Aerodynamisches Institut, RWTH Aachen.

Schmitz, S., Bhagwat, M., Moulton, M. A., Caradonna, F. X. and Chattot, J.-J.

"THE PREDICTION AND VALIDATION OF HOVER PERFORMANCE AND DETAILED BLADE LOADS"

Journal of the American Helicopter Society, Vol. 54, No. 3, July 2009, pp. 32004-1 - 32004-12.

This paper focuses on the validation of a hybrid computational fluid dynamics (CFD) method for the prediction of isolated rotor hover performance of the model UH-60A and tapered-tip variant rotors by comparison with available data sets. The hybrid method combines a local Reynolds-averaged Navier-Stokes solver to resolve the near-blade flow, with a vorticity-embedding potential flow solver for the wake flow field. The comparisons entail wake trajectories, surface pressures, integrated sectional thrust and torque, and rotor performance. The wake and loads comparisons demonstrate that the current method has a predictive accuracy and speed that is unusual to most CFD methods. The resulting performance comparisons are inconclusive owing partially to the fact that two available data sets do not agree to the level of accuracy required for validation. It appears therefore that development of hover CFD methods requires validation and test data in greater detail and variety than currently exists.

Schneemann, J., Trabucchi, D., Trujillo, J. J. and Kuhn, M.

"COMPARING MEASUREMENTS OF THE HORIZONTAL WIND SPEED OF A 2D MULTI-LIDAR AND A CUP ANEMOMETER"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012091-1 - 012091-8.

Wind measurements of a 2D Multi-Lidar and a mast mounted cup anemometer are compared in this study. Average wind speed and direction as well as the turbulence intensity of the wind speed are considered. Data analysis is mainly performed using standard regression analysis on 10-minute average data and the calculation of the power spectral density. The results show a good agreement regarding wind speed and direction and the turbulence intensity of the horizontal wind.

Schoenfeld, T., Corjon, A., Rudnik, R., Ronzheimer, A, Elphick, G. and Galpin, S.

"WAKE VORTEX ANALYSES OF A HIGH-LIFT AIRCRAFT CONFIGURATION ON STRUCTURED AND UNSTRUCTURED GRIDS"

AIAA Paper No. 2000-2218, Denver, CO, June 2000

The numerical simulation of the vortical flow field behind a generic high-lift wing-fuselage-flaps-slat aircraft configuration is presented. Vortex formation at the trailing edge and the wing tips and their spatial evolution in the near field are investigated. The 3D Euler equations are solved on both block-structured and unstructured grids. The evaluation of the computational results is done by assessing the simulation quality through comparison with experimental PIV data and computational results between the different partners of the European EuroWake project.

Schoenhals, S., Steen, M. and Hecker, P.

"TOWARDS WAKE VORTEX SAFETY AND CAPACITY INCREASE: THE INTEGRATED FUSION APPROACH AND ITS DEMANDS ON PREDICTION MODELS AND DETECTION SENSORS"

ICAS 2010 Paper 2010-11.6.3, Sept. 2010, Nice, France.

The integrated concept for collaboration of wake vortex prediction and measurement is introduced in this paper. This approach can increase airport and air space capacity while maintaining or even improving current wake vortex safety. The aspect of requirements resulting for the prediction model and measurement sensor is presented in detail. Implementation examples are given for ease of understanding.

Schoennhals, S., Steen, M. and Hecker, P.

"ENHANCING WAKE VORTEX SURVEILLANCE CAPABILITY USING INNOVATIVE FUSION APPROACHES"

Paper EN-048, Second ENRI International Workshop on ATM/CNS, EIWAC 2010, November 2010, Tokyo, Japan.

A new concept for collaboration of wake vortex prediction and measurement is introduced in this paper. This approach can enhance wake vortex surveillance capability of both airborne and ground wake vortex warning or avoidance systems. Thus, a significant step towards the increase of airport and air space capacity while maintaining or even improving current wake vortex safety could be achieved. Following an overview of the model and sensor components the fusion concept is being described. Implementation examples are given for ease of understanding.

Scholl, R. H., Buxel, C. and Neuwerth, G.

"INFLUENCE OF SPANWISE LOADING AND FINS ON EXTENDED NEAR-FIELD VORTEX WAKE"

AIAA Paper No. 2006-62, Reno, NV, January 2006.

The hazard imposed on aircraft by the wake vortices of leading aircraft persists to be a problem for airplane operations on highly-frequented airstrips. To develop a better understanding of the roll-up process of the vortices shed by a transport aircraft wing in different high-lift configurations, experimental investigations in a water tunnel are conducted. The wing is also equipped with a fin on the suction side. Velocities in the extended near-field up to four spans downstream of the wing are measured with Stereo Particle Image Velocimetry (SPIV). Different flap and fin settings are employed, and the effects on roll-up and meandering of the vortices are observed. Data are captured in a time-resolved fashion, and flow properties are determined from instantaneous as well as averaged velocity fields. The effect of vortex meandering on those properties is examined. It is found that the influence of fins on statical induced rolling moment is minimal. However, fins do prove to increase the meandering amplitude of the wake vortices, which decreases the actual hazard to following aircraft through dynamic effects.

Scholl, R., Henke, R. and Neuwerth, G.

"VORTEX SHEETS OF AIRCRAFT IN TAKEOFF AND LANDING"

Flow Modulation and Fluid-Structure Interaction, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 109, 2010, pp. 1-21.

In the present paper the development of vortex wake starting from the vortex sheet at the trailing edge of a transport aircraft wing up to the far field over 60 spans downstream is investigated. Different configurations of a half model were investigated in wind and water tunnels as well as in a towing tank by hot-wire anemometry and particle image velocimetry. In addition to an understanding of the development of the wake, means for the attenuation of the impact on following aircraft were investigated. A fin was installed on the suction side of the wing to investigate the impact on the vortex system downstream. The possibility of exploiting short-wave cooperative instabilities to accelerate vortex decay were investigated as well. This included active excitation of instabilities via ailerons oscillated in antiphase.

Scholte, J. J., van Baren, G. B. and Stroeve, S. H.

"QUALITATIVE SAFETY ASSESSMENT OF THE ATC-WAKE OPERATION"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

New and advanced Air Traffic Management systems and procedures are being developed for busy airports to cope with the increase in air traffic. The ATC-Wake project for the European Commission proposes an operation in which airport capacity is improved using dynamic weather-based aircraft separation standards, using an advanced ATC-Wake system. The current study lays a foundation for the

safety and capacity analysis of the ATC-Wake operation by providing a qualitative safety assessment of potential risks associated with the proposed operations. Potential safety bottlenecks identified in this study give early-stage feedback to operation designers and provide focusing points for subsequent safety modelling and quantitative safety assessment in the ATC-Wake project. The risks associated with the ATC-Wake operation were assessed using NLR's qualitative safety assessment methodology. This methodology is largely based on structured use of operational experts' judgement. The applied risk criteria are based on ESARR 4 requirements, using the ESARR 4 severity classification scheme and the ESARR 4 maximum tolerable probability of an accident, plus some additional assumptions that had to be made for this qualitative risk assessment. The risks of the proposed ATC-Wake operations were assessed for single runway arrivals, single runway departures and closely spaced parallel runway arrivals. In various brainstorming sessions with operational experts, 228 hazards were identified that might occur in the considered operations. These hazards were structured into 11 conflict scenarios, which aim to cover all imaginable ways in which the hazards can lead to or worsen a conflict situation. Using operational experts' judgement and knowledge from other studies, for each of these conflict scenarios the severity and the frequency of occurrence were assessed. Based on these severity and frequency assessments, and the risk criteria, an evaluation of the acceptability of the risk of each conflict scenario was given. The presentation will give a broad overview of the steps of the qualitative safety assessment, the safety criteria adopted and the main risk assessment results of the conflict scenarios identified.

Schonfeld, A., Luckner, R. and Efremov, A. V.

"A METHOD FOR INVESTIGATION OF PILOT-VEHICLE SYSTEM DYNAMICS IN WAKE VORTEX ENCOUNTERS"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-332, September 2007, pp. 1323-1332

One of the most hazardous external disturbances for civil and military aircraft is a severe wake vortex encounter. Primary effect on a trailing aircraft is the induced rolling moment. Depending on the encounter conditions also a noticeable reaction around the pitch axis can occur. Investigation of such incidents in flight tests depends on environmental conditions and can be quite expensive. For minimizing these factors and to reduce development time, it is desired to simulate the pilot-vehicle system reaction in ground simulation first. In this paper an approach is presented to model dual-axis pilot behavior during a wake vortex encounter in manual flight. The Modified Optimal Control Model (MOCM) was chosen to represent the pilot dynamics and for prediction of pilot-vehicle system responses in such a surprising case. Since the model requires a continuous input signal for parameterization, the assumption was made that manual control is carried out first in turbulent atmosphere. Adapted to the turbulence signal, the aircraft flies into the wake vortex and the pilot starts reacting to the turbulence, not changing his stereotype immediately. Experimentally obtained operator results successfully demonstrate the applicability of this extrapolation for the first half oscillation of the wake vortex signal. Besides linear aircraft dynamics, experiments have been executed for nonlinear actuator dynamics, too.

Schonfeld, T.

"12 YEARS OF EUROPEAN WAKE VORTEX RESEARCH AN OVERVIEW"

ECCOMAS CFD 2006: Proceedings of the European Conference on Computational Fluid Dynamics, September 2006, Egmond aan Zee, Netherlands.

This note contains the opening remarks for the dedicated wake vortex session held in the ECCOMAS CFD 2006 conference. A high-level description and associated background of the European wake turbulence research from 1994 to 2006 were provided. A few industry-wide focused research efforts provided tremendous physical insight on the physics of wake turbulence, but also the recognition of the limitation of classical wind tunnel techniques for advancing knowledge of the full wake life span. From there on, the European Commission launched several pan-European programs to understand topics ranging from the physical aspects for wake flows, verification of the level of safety in the system, wake instrumentation and detection techniques and stakeholder engagement forum.

Schonfeld, T., Boussuge, J.-F., Le Dizes, S. and Leweke, T.

"FUNDAMENTAL VORTEX PHENOMENA: INSTABILITIES AND INTERACTIONS WITH JETS AND WAKES"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-007, September 2007, pp. 1017-1025.

In this contribution, a synthesis of the recent results obtained in the frame of the ongoing European FP6 project FAR-Wake (Fundamental Research on Aircraft Wake Phenomena, 2005-2008), is presented. The main objective of this upstream research project is to gain better knowledge about open issues of vortex dynamics relevant to aircraft wakes, by investigating the following main topics, each treated in a separate work package: 1) the role of vortex instabilities on wake decay, 2) the influence of engine jets and of the turbulent wakes behind different aircraft components, and 3) the influence of ground effects, relevant for the wake evolution in the airport environment. The present paper deals with the first two topics, results from the work package on ground effects are shown in a different CEAS 2007 session on 'Wake Vortex Advisory Systems'.

Schonhals, S., Steen, M. and Hecker, P.

"WAKE VORTEX PREDICTION AND DETECTION UTILISING ADVANCED FUSION FILTER TECHNOLOGIES"

The Aeronautical Journal, Vol. 115, No. 1166, April 2011, pp. 221-228.

Because of its aerodynamic lift, each aircraft is generating wake vortices that can become a serious hazard for the succeeding aircraft and in the worst case lead to loss of control. Separation standards were introduced to prevent dangerous wake encounters that have proven sufficiently safe but also very conservative, thus limiting airspace and airport capacity. The objective of contemporary wake vortex research is regaining capacity in favorable atmospheric conditions, at the same time preserving or even improving the current safety level. The wake vortex advisory systems developed for this purpose are nearing experimental implementation and all include a forecasting component and additional online

detection sensors, with both elements having their benefits and limitations. The wake vortex research objectives at the Institute of Flight Guidance of the Technische Universität Braunschweig focus on a close coupling approach between model predictions and sensor measurements. Using the complementary capabilities of each, the aim of improved performance of the overall system shall be reached. After giving a short overview on the wake vortex phenomenon and current approaches to wake vortex alerting and advisory systems, this paper will introduce the fusion concept. The benefits of this approach will be demonstrated by means of examples. An outlook on further development and envisaged advanced implementation concepts will be given.

Schönhals, S., Steen, M. and Hecker, P.

"ENHANCING WAKE VORTEX SURVEILLANCE CAPABILITY USING INNOVATIVE FUSION APPROACHES"

ENRI International Workshop on ATM/CNS, Paper EN-048, Nov. 2010, Tokyo, Japan.

A new concept for collaboration of wake vortex prediction and measurement is introduced in this paper. This approach can enhance wake vortex surveillance capability of both airborne and ground wake vortex warning or avoidance systems. Thus, a significant step towards the increase of airport and air space capacity while maintaining or even improving current wake vortex safety could be achieved. Following an overview of the model and sensor components the fusion concept is being described. Implementation examples are given for ease of understanding.

Schönhals, S., Steen, M. and Hecker, P.

"SURVEILLANCE SYSTEMS ON-BOARD AIRCRAFT: PREDICTING, DETECTING AND TRACKING WAKE VORTICES"

8th Innovative Research Workshop and Exhibition, December 2009, EuroControl Experimental Centre, Bretigny-sur-Orge, France.

Capacity limitations due to conservative wake vortex separations can only be avoided by changes of the existing regulations. For the future, even the complete delegation of separation responsibility to the pilot is projected. This is only possible if safe operations are still guaranteed. For this purpose, methods for detection and prediction of wake vortices are developed. This paper presents a concept that allows taking advantage of the two different approaches by means of collaboration and use of fusion filters. The introduction of the fusion approach is subject of this article. Examples and results of the implemented possibilities are given and an implementation in an airborne environment is depicted. Future work and further developments of the system is addressed.

Schönhals, S., Steen, M. and Hecker, P.

"TOWARDS WAKE VORTEX SAFETY AND CAPACITY INCREASE: THE INTEGRATED FUSION APPROACH AND ITS DEMANDS ON PREDICTION MODELS AND DETECTION SENSORS"

Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol. 227, No. 1, January 2013, pp. 199-208.

Wake vortices and the prevention of wake vortex encounters are both an issue of safety and capacity in today's air transportation system. Current wake vortex separations are safe but also very conservative and thus have an adverse effect on capacity of airports. This article deals with the concept of fused wake vortex prediction and detection with the objective to deliver wake vortex strength and position with a high level of accuracy and reliability. The collaboration approach aims at fusion of models and sensors available for forecast and detection of hazardous wake turbulence to improve the overall system performance using the complementary capabilities of the single components. Different methods of coupling models with measurements are introduced and resulting the aspect of requirements for the prediction model and measurement sensor is presented. The implementation of an error-state system is presented and compared to sole prediction and sole sensor results. The results indicate that the fusion approach delivers benefits like reduced uncertainty of prediction and increased availability of detection and thus has the ability to increase airport and air space capacity while maintaining or even improving current wake vortex safety.

Schooley, A. H.

"WAKE COLLAPSE IN A STRATIFIED FLUID"

Science, Vol. 157, No. 3787, July 1967, pp. 421-423

A two-dimensional model is used to obtain quantitative data on characteristics of turbulently mixed wakes of bodies submerged in stratified fluids. The time between turbulent mixing and maximum expansion of the wake before vertical collapse starts is $0.44T$, where T is the local Vaisala-Brunt period. Time after mixing for maximum rate of horizontal spreading is about $2.0T$. Qualitative observations of aircraft vapor trails tend to confirm that the phenomenon does occur at full scale.

Schoppa, W.

"GENESIS OF LONGITUDINAL VORTICES IN NEAR-WALL TURBULENCE"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

Using direct numerical simulations of turbulence near one wall of a channel flow, we present a new linear instability mechanism for generation of near-wall longitudinal vortices in turbulent boundary layers. We formulate a two-dimensional base flow, containing no x -dependence or streamwise vorticity, to represent the streaks of low-speed fluid known to be prevalent near the wall. Linear instability is indicated by sustained exponential growth of low-amplitude perturbations; evidence suggests that this streak instability is inviscid in nature, despite the proximity of a no-slip wall. We demonstrate that the instability mechanism is inherently 3D, driven by sinuous streak displacement (along the span) induced by elliptical streamwise vorticity layers and quite analogous to oblique instability in free shear flow. The 3D features of the generated vortices, including counterrotation, tilting in the (x,z) plane and staggering in x , also agree well with the deduced (dominant) coherent structures, suggesting that this mechanism is

a dominant agent of longitudinal vortex regeneration near the wall. These results suggest strategies for realistic, large-scale (in contrast to fragile MEMS) control of drag and heat transfer over bodies.

Schouten, G.

"MOMENTUM, PRESSURE, AND ENERGY IN THE TREFFTZ-PLANE"

J. Aircraft, Vol. 32, No. 5, September-October 1995, pp. 943-95.

The distributions of momentum and energy generated by a force working in a fluid together with the associated pressure distributions are discussed in detail. The momentum generated by an impulsive point force in a compressible atmosphere is identified for two-thirds in a moving virtual sphere of fluid and for one-third in a front expanding with the velocity of sound. In a transverse section of an incompressible atmosphere the net momentum is identically zero when boundary conditions are left out of the considerations. It is discussed where and how net momentum is imparted to the atmosphere by impulsive and steady, moving force distributions. The analogy between an actuator surface and a viscous boundary layer on a flat plate, both involving the generation of momentum in a definite jet or wake region, is discussed in the same frame of reference as the induced drag of a lifting wing. The boundary conditions on and the dimensions of the control box both play a role in the answer to the question if and where net momentum is to be found. The statement that the net momentum in a transverse section remains zero proves to be only approximately valid in a free atmosphere. An important conclusion is that at an overall scale the unsteady pressures in any model, viscous or nonviscous, dominate the momentum balance.

Schowalter, D. G., DeCroix, D. S., Lin, Y.-L., Arya, S. P. and Kaplan, M. L.

"THE SENSITIVITY OF LARGE-EDDY SIMULATION TO LOCAL AND NONLOCAL DRAG COEFFICIENTS AT THE LOWER BOUNDARY"

NASA-CR-198310, April 1996, North Carolina State University, Raleigh, NC

This work is part of a program to predict aircraft wake vortex behavior under various meteorological conditions within the planetary boundary layer. It was found that the homogeneity of the surface drag coefficient plays an important role in the large-scale structure of turbulence in large-eddy simulation of the convective atmospheric boundary layer. Particularly when a ground surface temperature was specified, large horizontal anisotropies occurred when the drag coefficient depended upon local velocities and heat fluxes. This was due to the formation of streamwise roll structures in the boundary layer. In reality, these structures have been found to form when shear is approximately balanced by buoyancy. The present cases, however, were highly convective. The formation was caused by particularly low values of the drag coefficient at the entrance to thermal plume structures.

Schowalter, D. G., DeCroix, D. S., Switzer, G. F., Lin, Y.-L., and Arya, S. P.

"TOWARD THREE-DIMENSIONAL MODELING OF A WAKE VORTEX PAIR IN THE TURBULENT PLANETARY BOUNDARY LAYER"

AIAA Paper No. 1997-0058, Reno, NV, January 1997

A method for large-eddy simulation of aircraft wake vortices embedded in planetary boundary turbulence is outlined. A nested grid scheme and three-dimensional initial and boundary conditions are described and demonstrated. The nested grid scheme allows multiple one-way or two-way simulations using mass-conservative interpolation and averaging schemes along with radiative boundary conditions which lets unwanted wave energy pass out of the finer mesh domains. The three-dimensional wake vortex initial and boundary conditions force fully-developed wake vortices on the upstream boundary but permit the vortices within the domain to develop spatially and temporally. Future work will entail combining the two schemes for simulations of wake vortices embedded within the convective planetary boundary layer.

Schrader, M. L.

"CALCULATIONS OF AIRCRAFT CONTRAIL FORMATION CRITICAL TEMPERATURES"

Journal of Applied Meteorology, Vol. 36, 1997, pp. 1725-1729.

Forecasts of condensation trail (contrail) formation are an extremely important consideration in military aircraft operations, particularly in the operation of stealth aircraft. Some recently published works have claimed improvements in the time-tested forecast technique of H. Appleman, but the results are called into question by errors in the basic physics. This note provides a brief explanation of contrail formation theory and presents a simple derivation of the critical temperature of contrail formation for representative jet engine types.

Schram, C., Hirschberg, A. and Verzicco, R.

"SOUND PRODUCED BY VORTEX PAIRING: PREDICTION BASED ON PARTICLE IMAGE VELOCIMETRY"

AIAA Journal, Vol. 42, No. 11, Nov. 2004, pp. 2234-2244.

In some cases, the prediction of the sound generated by flows is impaired by inaccuracies in the available flow data. These inaccuracies can be due to the degree of approximation of a flow model, or to the uncertainty of a measurement technique. A particular crucial point for sound prediction is the conservation of the flow invariants. The sound radiated by vortex pairing in a subsonic excited jet is deduced from experimental data obtained by particle image velocimetry. The performance is compared of different formulations of vortex sound theory to predict the corresponding sound production. It is shown that assuming several times the conservation of the momentum and kinetic energy in the implementation of the vortex sound theory improves considerably the robustness of the prediction. In fact, a prediction in good agreement with both a theoretical model of leapfrogging and numerical simulations of merging is obtained, although the basic data do not respect precisely these conservation laws.

Schroder, A. and Konrath, R.

"REDUCING CIRCULATION IN A WAKE TURBULENCE BEHIND AN AIRPLANE FLYING AT LOW ALTITUDE"

US Patent 2011/0210202 A1, September 2011.

For reducing a circulation of wake vortexes in a wake turbulence behind an airplane flying over ground at low altitude, at least one ring vortex of airflow is generated at the ground on each side of a vertical middle plane of the airplane. Each ring vortex has a vortex axis and a direction of propagation, wherein the vortex axis is oriented at an angle with respect to the ground and wherein the propagation direction is oriented upwards from the ground, and each ring vortex disturbs at least one wake vortex to induce its decay.

Schroder, A. and Konrath, R.

"REDUCING CIRCULATION IN A WAKE TURBULENCE BEHIND AN AIRPLANE FLYING AT LOW ALTITUDE"

US Patent 8,528,858 B2, September 2013.

For reducing a circulation of wake vortexes in a wake turbulence behind an airplane flying over ground at low altitude, at least one ring vortex of airflow is generated at the ground on each side of a vertical middle plane of the airplane. Each ring vortex has a vortex axis and a direction of propagation, wherein the vortex axis is oriented at an angle with respect to the ground, and wherein the propagation direction is oriented upwards from the ground; and each ring vortex disturbs at least one wake vortex to induce its decay.

Schroder, W., Thomer, O. and Krause, E.

"STRONG SHOCK -- VORTEX INTERACTION -- A NUMERICAL STUDY"

ICTAM04 Proceedings, Mechanics of the 21st Century, August 2004, Warsaw, Poland.

The intersection of a longitudinal vortex by a normal shock is studied with a numerical solution of the Euler and Navier-Stokes equations for time-dependent, three-dimensional, laminar flow. The study is concerned with the destruction of the vortex core, usually referred to as vortex breakdown or bursting, by letting the shock intersect the vortex normal to its axis. Results are presented for a Mach number about 1.6. The calculations were performed on a Cartesian mesh with approximately 2 million grid points. The computations show noticeable differences between the two solutions, and viscous forces become important in the burst part of the vortex. Visualization studies clearly reveal the time-dependent, three-dimensional nature of the flow after breakdown.

Schroeder, N.

"ANALYSIS OF POTENTIAL WAKE TURBULENCE ENCOUNTERS IN CURRENT AND NEXTGEN FLIGHT OPERATIONS"

MS Thesis, January 2011, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Wake vortices pose a threat to a following aircraft, because they can induce a roll and compromise the safety of everyone on board. Caused by a difference in pressure between the upper and the lower part of the wings, these invisible flows of air are a major hazard and must be avoided by separating the aircraft at considerable distances. One of the known constraints in airport capacity for both departure and arrival operations is the large headway resulting from the wake spacing separation criteria. Reducing wake vortex separations to a safe level between successive aircraft can increase capacity in the National Airspace System (NAS) with corresponding savings in delay times. One of the main goals of the Wake Encounter Model (WEM) described in this thesis is to assess the outcome from future reduced separation criteria in the NAS. The model has been used to test probable encounters in today's operations, and can also be used to test NextGen scenarios, such as Close Parallel Approaches and reduced in-trail separation flights. This thesis presents model enhancements to account for aircraft turning maneuvers, giving the wake a more realistic shape. Three major airspaces, New York, Southern California, and Atlanta, were analyzed using the original and the enhanced WEM to determine if the enhanced model better represents the conditions in today's operations. Additionally, some analysis on the wake lateral travel for closely spaced runways is presented in this thesis. Finally, some extension tools for post-analysis, such as animation tool and various graphs depicting the interactions between wake pairs were developed.

Schumann, U.

"FORMATION, PROPERTIES AND CLIMATIC EFFECTS OF CONTRAILS"

C. R. Physique, Vol. 6, 2005, pp. 549-56.

Condensation trails (contrails) are aircraft induced cirrus clouds, which may persist and grow to large cirrus cover in ice-supersaturated air, and may cause a warming of the atmosphere. This paper describes the formation, occurrence, properties, and climatic effects of contrails. The global cover by lined-shaped contrails and the radiative impact of line-shaped contrails is smaller than that assessed in an international assessment in 1999. Contrails trigger contrail cirrus with far larger coverage than observed for line-shaped contrails, but still unknown radiative properties. Some model simulations indicate an impact of particles and particle precursors emitted from aircraft engines on cirrus clouds properties. However, the magnitude of this effect cannot yet be assessed. Contrail formation can be avoided only by flying in sufficiently warm and dry air. The formation of contrail cirrus can be reduced by avoiding flights in ice-supersaturated regions of the atmosphere, e.g., by raising the flight level into the lower-most stratosphere.

Schumann, U.

"A CONTRAIL CIRRUS PREDICTION MODEL"

A new model to simulate and predict the properties of a large ensemble of contrails as a function of given air traffic and meteorology is described. The model is designed for approximate prediction of contrail cirrus cover and analysis of contrail climate impact, e.g. within aviation system optimization processes. The model simulates the full contrail life-cycle. Contrail segments form between waypoints of individual aircraft tracks in sufficiently cold and humid air masses. The initial contrail properties depend on the aircraft. The advection and evolution of the contrails is followed with a Lagrangian Gaussian plume model. Mixing and bulk cloud processes are treated quasi analytically or with an effective numerical scheme. Contrails disappear when the bulk ice content is sublimating or precipitating. The model has been implemented in a 'Contrail Cirrus Prediction Tool' (CoCiP). This paper describes the model assumptions, the equations for individual contrails, and the analysis-method for contrail-cirrus cover derived from the optical depth of the ensemble of contrails and background cirrus. The model has been applied for a case study and compared to the results of other models and in-situ contrail measurements. The simple model reproduces a considerable part of observed contrail properties. Mid-aged contrails provide the largest contributions to the product of optical depth and contrail width, important for climate impact.

Schumann, U. and Sharman, R.

"AIRCRAFT WAKE-VORTEX ENCOUNTER ANALYSIS FOR UPPER LEVELS"

Journal of Aircraft, Vol. 52, No. 4, July-August 2015, pp. 1277-1285.

The frequency of aircraft encountering the wake of other aircraft is analyzed for given aircraft, movement, and meteorological data. The method considers the descent and decay of wake vortices for a given stratification and turbulence-kinetic-energy dissipation rate, and the advection with ambient horizontal and vertical wind. An encounter is characterized in this study by the distance between the position of a follower aircraft and the centerline of a wake vortex behind the vortex generator, and by the wake-induced lift forces or roll moments on the encountering aircraft. A linear model is used for an efficient identification of potential wake-vortex encounters for all flight segments in dense traffic regions. The method is applied to radar-observed traffic over North America in 46 days in 2010/2011, and validated against pilot-reported wake encounters and automated in situ turbulence reports. Most upper-level encounters are found for medium-size aircraft on nearly parallel flight routes during descent. En route encounters of wakes from heavy aircraft flying 1000 ft higher occur relatively rarely. The frequency of wake-vortex encounters increases with the square of air-traffic density.

Schumann, U., Dornbrack, A., Durbeck, T. and Gerz, T.

"LARGE-EDDY SIMULATION OF TURBULENCE IN THE FREE ATMOSPHERE AND BEHIND AIRCRAFT"

Fluid Dynamics Research, Vol. 20, Issues 1-6, February 1997, pp. 1-10

The method of large-eddy simulation has been used for a wide variety of atmospheric flow problems. This paper gives an overview on recent applications of this method to turbulence in the free

atmosphere under stably stratified conditions. In particular, flows in the wake of aircraft are studied considering the potential impact of aircraft exhausts on the chemical and climatological state of the atmosphere. It is shown that different profiles of heat and moisture in the initial conditions of a jet representing engine exhaust gases may cause larger water saturation and hence earlier contrail formation than assumed up to now. The instability of trailing vortices in the wake of an aircraft is simulated up to the fully turbulent regime. The vertical diffusivity of aircraft exhaust is large in the vortex regime and much smaller than horizontal diffusivities in the later diffusion regime. The three-dimensional formation of a critical layer and breaking of gravity waves is simulated.

Schumann, U., Graf, K., Mannstein, H. and Mayer, B.

"CONTRAILS: VISIBLE AVIATION INDUCED CLIMATE IMPACT"

In: Atmospheric Physics, Research Topics in Aerospace, U. Schumann (editor), Springer-Verlag Berlin Heidelberg, 2012, pp. 239-257.

Contrails are aircraft induced linear ice particle clouds. In ice-supersaturated air masses, contrails persist and develop into contrail cirrus. Aviation changes cloudiness also by soot emissions and other aerosols. In the global mean, contrail cirrus warms the atmosphere. The local warming induced by a contrail varies strongly relative to the global mean, and may be positive or negative, depending on aircraft, route, solar and Earth-atmosphere parameters. Here we summarize present knowledge on contrails with respect to aviation and atmospheric research.

Schunk, C., Bahlman, J. W., Swartz, S. M. and Breuer, K. S.

"MEASUREMENT OF THE WAKE BEHIND A BAT-LIKE FLAPPER AND THE INFLUENCE OF THE FLAPPING FREQUENCY ON LIFT GENERATION"

AIAA Paper No. 2011-3116, June 2011, Honolulu, Hawaii.

The wake structure behind a simplified flapping model based on the Lesser short-nosed fruit bat *Cynopterus brachyotis* was examined at a Reynolds number $Re \sim 30000$ and four Strouhal numbers between 0.014 and 0.126 using high speed PIV in the Trefftz plane. Besides the tip vortex, three other vortex structures were observed at higher Strouhal numbers: a proximal counter rotating vortex, indicating that over the body temporarily no lift is produced, and a distal vortex dipole, showing that the distal part of the wing is generating negative lift during the upstroke at higher Strouhal numbers. Even though real bats cruise at higher Strouhal numbers (greater than or equal to 0.2), the same four vortices were described for the wake structures of three different bat species.

Schutte, A.

"NUMERICAL INVESTIGATIONS OF VORTICAL FLOW ON SWEEPED WINGS WITH ROUND LEADING EDGES"

Journal of Aircraft, Vol. 54, No. 2, March-April 2017, pp. 572-601.

The present work is investigating the vortex-dominated flow physics as well as the aerodynamic behavior of swept wing configurations with round leading edges. The research is based on numerical simulations using the computational fluid dynamics method DLR TAU. The target configurations are swept wings of constant aspect ratio, variable leading-edge contours, and leading-edge sweep angles. The work deals with the onset of the vortical flow at the leading edge for constant and variable leading-edge nose radii, the influence of the angle of attack, the leading-edge sweep, and the onflow Mach number. Furthermore, the aerodynamic behavior is analyzed and assessed, as well as the specific flow physics in the vicinity of the vortical flow separation at round leading edges. The objective of the present work is to provide a contribution for the design and assessment of the physical characteristics of swept wing configurations. Furthermore, sensitivities will be given for the design process. In addition, the current investigation provides a deeper understanding of the separation onset process and the flow physics of swept wing configurations with round leading edges.

Schwaiger, H. F., Iezzi, A. M. and Fee, D.

"AVO-G2S: A MODIFIED, OPEN-SOURCE GROUND-TO-SPACE ATMOSPHERIC SPECIFICATION FOR INFRASOUND MODELING"

Computers & Geosciences, Vol. 125, April 2019, pp. 90-97.

To facilitate infrasound propagation studies, we present AVO-G2S, an open-source, Ground-to-Space model which provides temperature and wind specifications from the surface to an altitude of 225km. This model provides a means of smoothly characterizing atmospheric conditions using multiple numerical weather prediction forecast and reanalysis products, along with upper-atmospheric empirical models. Regional atmospheric reconstructions only require a limited domain and can utilize high-resolution numerical weather prediction forecasts typically provided on a projected grid. The use of a projected grid allows for faster spectral transform libraries to be employed. The AVO-G2S software can also provide global reconstructions that rely on global numerical weather prediction products and spherical harmonic decompositions. AVO-G2S is inspired by a global Ground-to-Space model developed by the Naval Research Laboratory, and relies on their empirical descriptions of upper-atmospheric conditions. Alaska Volcano Observatory has implemented this model for near-real-time infrasound monitoring of volcanic eruptions and historical research projects.

Schwartz, B. and Benjamin, S. G.

"A COMPARISON OF TEMPERATURE AND WIND MEASUREMENTS FROM ACARS-EQUIPPED AIRCRAFT AND RAWINSONDES"

Weather and Forecasting, Vol. 10, September 1995, pp. 528-544.

A comparison was made of temperature and wind observations reported by rawinsonde and Aircraft Communications, Addressing, and Reporting System (ACARS)-equipped commercial aircraft separated by less than 150 km in distance and 90 min in time near Denver, Colorado, in February and March 1992. Only data made on aircraft ascents and descents reported automatically were used. A total of 4440

matched data pairs were obtained for this period. The sample was analyzed in total but also as a function of time and distance separation, height, time of day, and ascent versus descent. A standard deviation temperature difference of 0.97 degrees C and rms vector wind difference of 5.76 m/s were found for the entire sample but were reduced, respectively, to 0.59 degrees C and 4.00 m/s when only data pairs separated by less than 25 km and 15 min were used. The study provides an upper limit to the combination of rawinsonde and ACARS observation and reporting errors and mesoscale variability, but it is not possible to distinguish the exact combinations from each of these sources. However, overall, these statistics indicate that the rawinsonde data used were more accurate than that reported in a previous study and that the accuracy of the ACARS data was somewhat higher still.

Schwarz, C.

"SCENARIO DEFINITIONS"

CREDOS Report D3-3, September 2007, DLR, Oberpfaffenhofen, Germany.

CREDOS subtask 3.1.3 and this report provide a definition of wake vortex encounter scenarios during the takeoff phase as a basis for the simulations carried out in CREDOS. The parameters of influence for wake vortex encounters during takeoff are discussed and offline wake vortex encounter simulations are conducted to derive tendencies for the impact of relevant parameters.

Schwarz, C. and Fischenberg, D.

"ANALYSIS OF TWO 2005 WAKE VORTEX ENCOUNTER INCIDENTS"

ICAS 2010, Paper 2010-10.2.1, Sept. 2010, Nice, France.

Two potential wake vortex encounter incidents (medium behind heavy) are subject to investigation (radar data, FDR data, meteo data). The wake vortex behavior is simulated to estimate the closest proximity to the wake vortex indicating that a wake encounter with considerable vortex strength is likely in both cases.

Schwarz, C. and Fischenberg, D.

"WAKE TURBULENCE HAZARD ANALYSIS FOR A GENERAL AVIATION ACCIDENT"

Document 340177, December 2014, DLR, Braunschweig, Germany.

Whereas wake turbulence is commonly a topic within commercial aviation which is involving large/heavy transport aircraft, there can also be a hazard for general aviation flight operations. This has been investigated for a specific case of an accident where an aircraft of class E (one engine with a maximum takeoff weight up to 2 tons) took off behind an aircraft with 5.5 tons maximum takeoff weight. Based on available information and several assumptions the potential wake turbulence situation for the specific aircraft combination has been assessed. The roll axis was the dominating factor in this case. Accordingly, the wake induced rolling moment was analyzed and related to the

assumed available roll control power. Furthermore, the wake vortex behavior was simulated. The results indicate that wake turbulence can likely be the main reason for the accident.

Schwarz, C. and Hahn, K.-U.

"AUTOMATED PILOT ASSISTANCE FOR WAKE VORTEX ENCOUNTERS"

Aerospace Science and Technology, Vol. 15, 2011, pp. 416-421.

Wake vortices pose a possible hazard for encountering aircraft in all phases of flight. Hence wake vortex encounters are to be avoided in any case. In case of an unintended wake vortex encounter, special aircraft controllers can act as a safety net. Such an active wake vortex control system is being developed by the DLR Institute of Flight Systems based on feed-forward disturbance compensation. The control system has been tested with offline and pilot-in-the-loop investigations as well as with flight tests. It can be shown that the aircraft response can be improved significantly if the pilots are supported by an automatic wake assistance system. For the subjective assessment of the wake vortex encounters a dedicated pilot rating scale has been developed. The results show a clear tendency that the wake vortex controller improves the situation.

Schwarz, C. and Hahn, K.-U.

"GEFAHRDUNG BEIM EINFLOGEN IN WIRBELSCHLEPPEN"

Deutsche Luft- und Raumfahrt-Kongress, Munich, Germany, November 2003

Estimation of the risk assessment for flying into wake vortices will be determined at the DLR Institute for Flight Technical Systems by developing a simulation system of the aircraft reaction. It will introduce a risk zone concept that will be checked against a completely nonlinear simulation system. The definition of the risk zone is made possible by determining at any given time the necessary minimum distance from the leading aircraft, allowing for a safe crossing of the wake flow. [In German.]

Schwarz, C. and Hahn, K.-U.

"HAZARD AREAS FOR WAKE VORTEX ENCOUNTER AVOIDANCE"

German Aerospace Congress 2004, Dresden, Germany, DGLR-JT2004-014 (in German)

For the hazard assessment of wake vortex encounters hazard zones are defined. If these are not violated a safe and undisturbed flight operation is possible. For the determination of the hazard zones the required roll control power is used. Its limit must be chosen in such a way that outside the hazard zone all wake vortex effects are noncritical. For the determination of such limits offline as well a full-flight simulator studies were conducted. By means of the 'Simplified Hazard Area Prediction (SHAPE)' method simplified hazard zones are calculated. By parameterization of the input values the hazard zone concept is applicable universally to different aircraft types. SHAPE represents an essential

element of the wake vortex prediction and observation system within the DLR project Wirbelschlepp II, for the generation of safe dynamic wake vortex separations.

Schwarz, C. and Hahn, K.-U.

"AUTOMATED PILOT ASSISTANCE FOR WAKE VORTEX ENCOUNTERS"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-005, September 2007, pp. 1001-1006.

Wake vortices pose a possible hazard for encountering aircraft in all phases of flight. Hence wake vortex encounters are to be avoided in any case. In case of an unintended wake vortex encounter, special aircraft controllers can act as a safety net. Such an active wake vortex control system is being developed by the DLR Institute of Flight Systems based on feed-forward disturbance compensation. The control system has been tested with offline and pilot-in-the-loop investigations as well as with flight tests. It can be shown that the aircraft response can be improved significantly if a specific wake vortex controller is active. For the subjective assessment of the wake vortex encounters a dedicated pilot rating scale has been developed. The results show a clear tendency that the wake vortex controller improves the situation.

Schwarz, C. and Hahn, K.-U.

"IMPACT OF INDIVIDUAL AND DYNAMIC WAKE VORTEX SEPARATIONS ON AIRPORT CAPACITY"

25th International Congress of the Aeronautical Sciences (ICAS-2006), Sept. 2006, Hamburg, Germany.

For many airports the capacity is limited by minimum separation distances especially for approach and landing due to the possible hazard generated by wake vortices. To alleviate capacity limitations, separation rules must be improved without reducing safety. Based on simplified hazard areas dynamic wake vortex separations can be derived considering atmospheric conditions and actual aircraft pairing. This concept is applied to parallel runways in comparison to the single runway case for cross wind and headwind conditions.

Schwarz, C. and Holzaepfel, F.

"SCENARIO DEFINITIONS"

CREDOS Report D3-3, September 2007, DLR, Braunschweig, Germany.

CREDOS subtask 3.1.3 and this report provide a definition of wake vortex encounter scenarios during the takeoff phase as a basis for the simulations carried out in CREDOS. The parameters of influence for wake vortex encounters during takeoff are discussed and offline wake vortex encounter simulations are conducted to derive tendencies for the impact of relevant parameters.

Schwarz, C. and Holzaepfel, F.

"THE CREDOS PROJECT: CREDOS SCENARIO DEFINITIONS"

D3-3, September 2007.

This report provides a definition of wake vortex encounter scenarios during the takeoff phase as a basis for the simulations carried out in CREDOS. The parameters of influence for wake vortex encounters during takeoff are discussed and offline wake vortex encounter simulations are conducted to derive tendencies for the impact of relevant parameters.

Schwarz, C. W. and Hahn, K.-U.

"SIMPLIFIED HAZARD AREAS FOR WAKE VORTEX ENCOUNTER AVOIDANCE"

AIAA Paper No. 2005-5903, San Francisco, CA, August 2005

Simplified hazard areas (SHA) can help to master the wake vortex problem. Avoiding these zones allows safe and undisturbed flight operations. The definition of the hazard areas is based on the nominal required roll control power. The limit for this value must be chosen carefully to ensure that outside the hazard area all wake vortex effects are noncritical. To identify such a limit, offline simulations, full flight simulator studies, and in-flight simulations were conducted. The hazard area dimensions for a specific roll control limit are derived with the 'Simplified Hazard Area Prediction' method (SHAPE). Parameterization of the input parameters makes this method universally applicable to different aircraft types. SHAPE represents a fundamental element of the wake vortex prediction and observation system within the interdisciplinary DLR project Wirbelschlepppe II, for the generation of safe dynamic wake vortex separations.

Schwarz, C. W. and Hahn, K.-U.

"FULL-FLIGHT SIMULATOR STUDY FOR WAKE VORTEX HAZARD AREA INVESTIGATION"

Aerospace Science and Tech., Vol. 10, 2006, pp. 136-143

Simplified hazard areas (SHA) can help to overcome the wake vortex problem. Avoiding these zones allows safe and undisturbed flight operations. The definition of the hazard areas is based on the nominal required roll control power. The nominal limit for this value must be chosen carefully to ensure that outside the hazard area all wake vortex effects are noncritical. For the determination of such a limit offline simulations and full flight simulator studies were conducted. For a given roll control limit the hazard area dimensions are established with the 'simplified hazard area prediction' method (SHAPE). Parameterization of the input parameters makes this method universally applicable to different aircraft types. SHAPE represents an essential element of the wake vortex prediction and observation system within the DLR project Wirbelschlepppe II, for the generation of safe dynamic wake vortex separations.

Schwarz, C. W., Fischenberg, D. and Holzaepfel, F.

"WAKE TURBULENCE EVOLUTION AND HAZARD ANALYSIS FOR A GENERAL AVIATION TAKEOFF ACCIDENT"

AIAA Paper 2018-3019, June 2018, Atlanta, GA.

Wake turbulence is commonly a commercial aviation topic involving relatively heavy transport aircraft. However, wake turbulence is also safety relevant for business and general aviation flight operations. A detailed analysis has been conducted for a specific accident involving two aircraft of the wake turbulence category light. A four-seat aircraft with one-ton maximum takeoff weight took off behind a biplane with 5.5 tons maximum takeoff weight. This led to a fatal accident. Based on available information and several assumptions the wake turbulence aspects for the specific accident scenario have been assessed. The roll axis was the dominating factor in this case. Accordingly, the wake induced rolling moment was analyzed and related to the assumed available roll control power. Furthermore, the wake vortex behavior was simulated and analyzed in detail. The results indicate that wake turbulence can be considered to be the cause for the accident. The theoretical results and the conclusions regarding the accident are also supported by the results of flight tests, which were conducted in the context of the accident investigation.

Schwarz, C. W., Hahn, K.-U. and Fischenberg, D.

"WAKE ENCOUNTER SEVERITY ASSESSMENT BASED ON VALIDATED AERODYNAMIC INTERACTION MODELS"

AIAA Paper No. 2010-7679, Toronto, Canada, August 2010.

Wake encounter severity criteria based on validated models are of great importance for any wake vortex related severity assessment. The aerodynamic interaction model 'strip method' describes the vortex-induced aircraft reaction. The model quality is validated with wake encounter flight test data. Model shortcomings are improved with dedicated refinements. A simplified hazard area approach is developed employing validated simulation models. With one simple criterion, the roll control ratio, safe and undisturbed flight operations can be ensured. A limit value for manually flown (non-fly-by-wire) aircraft is derived from piloted trials. With the simplified hazard area prediction method, this can be universally applied for wake vortex advisory systems like DLR's wake vortex prediction and monitoring system.

Schwarz, C., Bauknecht, A., Mailander, S. and Raffel, M.

"WAKE CHARACTERIZATION OF A FREE-FLYING MODEL HELICOPTER IN GROUND EFFECT"

AHS International 74th Annual Forum & Technology Display, May 2018, Phoenix, Arizona.

Measurements of the flow field around a free-flying model helicopter in ground effect for both quasi-steady and unsteady maneuvering flights were performed using stereoscopic particle image velocimetry (PIV). The wake features for hover and forward flight at low advance ratios were

characterized and changing flow patterns like circulation and ground vortex flow were observed to be in good agreement with existing wind tunnel data. Parameters describing both general flow patterns and single blade tip vortices were extracted and showed significant dependence on the forward flight velocity. Landing approaches were performed and large vortical structures were observed close to the rotor disk, which contained high amounts of vorticity due to entrained blade tip vortices. The vortex structures developing for unsteady landing approaches contained distinctly higher velocities and momentum fluxes than expected from quasi-steady conditions at the same advance ratios. For a vertical takeoff maneuver with a rapid increase of collective pitch, the bundling of blade tip vortices into a 'starting vortex' with circulation values up to 6 times higher than for a single blade tip vortex was observed. These results show the significance of experimental data on free-flying helicopters in unsteady maneuvering flight because the resulting flow fields cannot be predicted using steady-state experiments or simulations.

Schweiger, R. N.

"PULSED ACOUSTIC VORTEX SENSING SYSTEM, VOLUME IV: PAVSS PROGRAM SUMMARY AND RECOMMENDATIONS"

FAA-RD-74-19.4, June 1977, Avco, Wilmington, M.

An engineered Pulsed Acoustic Vortex Sensing System (PAVSS) was developed. This system is capable of real-time detection, tracking, recording, and graphic display of aircraft trailing vortices. This volume of the report summarizes the background and accomplishments of the PAVSS program carried out by Avco, and presents Avco's recommendation that further work on the PAVSS would not be economically sound.

Schweiger, R. N.

"PULSED ACOUSTIC VORTEX SENSING SYSTEM, VOLUME II: STUDIES OF IMPROVED PAVSS PROCESSING TECHNIQUES"

FAA-RD-74-19.2, June 1977, Avco, Wilmington, M.

AVCO Corporation's System Division designed and developed an engineered Pulsed Acoustic Vortex Sensing System (PAVSS). This system is capable of real-time detection, tracking, recording, and graphic display of aircraft trailing vortices. This volume of the report presents the results of two subcontractor studies directed toward development of improved vortex tracking software techniques for the PAVSS. The volume recommends the incorporation of several improvements in the software.

Schweiger, R. N.

"PULSED ACOUSTIC VORTEX SENSING SYSTEM, VOLUME III: PAVSS OPERATION AND SOFTWARE DOCUMENTATION"

FAA-RD-74-19.3, June 1977, Avco, Wilmington, M.

AVCO Corporation's System Division designed and developed an engineered Pulsed Acoustic Vortex Sensing System (PAVSS). This system is capable of real-time detection, tracking, recording, and graphic display of aircraft trailing vortices. This volume of the report presents the operation of the pulsed acoustic vortex sensing system and the computer software documentation.

Schweiger, R. N.

"PULSED ACOUSTIC VORTEX SENSING SYSTEM, VOLUME I: HARDWARE DESIGN"

FAA-RD-74-19.1, June 1977, Avco, Wilmington, M.

An engineered Pulsed Acoustic Vortex Sensing System (PAVSS) was developed. This system is capable of real-time detection, tracking, recording, and graphic display of aircraft trailing vortices. This volume of the report presents hardware design aspects of the system. The design of the acoustic antenna and transducer is described. System control, computer hardware, and system/subsystem hardware interfaces are discussed.

Scorer, R. S. and Davenport, L. J.

"CONTRAILS AND AIRCRAFT DOWNWASH"

J. Fluid Mech., Vol. 43, Part 3, September 1970, pp. 451-464

Aircraft downwash consists initially of a vortex pair descending with its accompanying fluid through the atmosphere. Condensation trails are formed in exhaust emitted into the accompanying fluid and the shapes of them and their evolution depend on the positions of the engines in relation to the wing tip vortices. The atmosphere is stably stratified and so the descending accompanying fluid acquires upward buoyancy. Consequently, vorticity is generated at the outside of the accompanying fluid and the flow pattern in the vortex pair is altered to produce detrainment of its exterior part. So long as any air which is a mixture of accompanying fluid and exterior air is detrained, the vortices remain stable, but the width of the pair decreases and its downward velocity increases with time because of the buoyancy. Eventually the upper stagnation point in the motion relative to the vortices begins to move upwards relative to the vortices so that some mixed fluid is entrained into the circulation and the vortices immediately become unstable, mixing occurs, the pressure in the core rises, and any vortex core trails that may exist appear to burst. The motion produces downward-thrust blobs in trails from centrally placed engines, which correspond to the holes sometimes seen in cloud when distrails are formed.

Scott, G. A.

"NEW HORIZONS IN AIR TRAFFIC CONTROL"

AIAA Paper No. 1975-0569, Boston, MA, 1975

According to the FAA's latest air traffic forecasts, aviation in the United States will continue to grow into the indefinite future. To meet the demands of this continuing growth, the existing air traffic control (ATC) system must be improved. The goals of the future upgraded ATC system are: maintain or improve safety, constrain or reduce costs, and increase and improve performance. These goals will be met in part by the following new ATC features -Airport Surface Traffic Control System (ASTC), Discrete Address Beacon System (DABS), Air Traffic Control Automation, Intermittent Positive Control (IPC), Area Navigation (RNAV), Microwave Landing System (MLS), and Wake Vortex Avoidance System (WVAS).

Scruggs, R. M. and Theisen, J. G.

"TRANSONIC BUFFET RESPONSE TESTING AND VORTEX CONTROL"

Proceedings of Symposium on Unsteady Aerodynamics, U.S. Air Force Office of Scientific Research and Univ. of Arizona, Vol. I, 1975, pp. 337-357

The basic theory of vortex stabilization by means of core wise blowing is presented as a vortex-lattice, source-induction (VLSI) computer simulation. An extension of Polhamus' leading-edge suction analogy to high aspect-ratio wing is derived, showing the effect of aspect ratio on near wake vortex burst.

Scully, M. P.

"A METHOD OF COMPUTING HELICOPTER VORTEX WAKE DISTORTION"

ASRL TR 138-1, June 1967, Massachusetts Institute of Technology, Cambridge, MA.

A method for computing the geometry of the tip vortex of a helicopter rotor in steady, forward flight, including the distortion due to the velocities induced by the vortex wake, has been developed. The relative importance of various parameters and approximations used by this method has been evaluated for one test case, including comparison with experimental results obtained from a flow visualization study.

Scully, M. P.

"COMPUTATION OF HELICOPTER ROTOR WAKE GEOMETRY AND ITS INFLUENCE ON ROTOR HARMONIC AIRLOADS"

PhD Thesis, February 1975, Massachusetts Institute of Technology, Cambridge, MA.

Efficient techniques are developed for the computation of helicopter rotor tip vortex geometry and helicopter rotor harmonic airloads. These techniques are designed to minimize the computational expense by the use of simplified wake models together with other devices which reduce the amount of integration over the wake of the Biot Savart relation for induced velocity. These techniques are designed for use in steady-state flight at advance ratios below 0.3; however, they could be readily extended to higher advance ratios and to transient flight conditions. The results of the tip vortex geometry computations show that, over the forward portion of the rotor, the tip vortex is much closer

to the rotor than the classical rigid wake assumption would indicate. This results in very intense, close blade-tip vortex interactions. These interactions must be modeled much more carefully than the less intense ones which occur when the rigid wake geometry assumption is used. The use of a lifting-surface solution for the airloads induced by these close blade-tip vortex interactions resulted in a substantial improvement in the agreement with measured airloads. Further improvement was obtained by the use of a very simplified model for tip vortex-core bursting and for the propagation of that bursting ahead of the blade which initiated it. This, together with the lifting-surface solution, brought the computed airloads into reasonable agreement with the measured airloads. A simple tip vortex roll-up model was used to test the effect of roll-up on the airloads computation and it was found to be significant in some cases. The effects of tangentially-induced velocity and local separation on airloads computations were also evaluated and found to be of limited importance. It is recommended that close blade-vortex interactions and tip vortex formation and roll-up be studied both experimentally and theoretically. The currently available knowledge of these phenomena is inadequate for accurate harmonic airloads computations.

Scully, M. P.

"COMPUTATION OF HELICOPTER ROTOR WAKE GEOMETRY AND ITS INFLUENCE ON ROTOR HARMONIC AIRLOADS"

ASRL TR 178-1, March 1975, Massachusetts Institute of Technology, Cambridge, MA.

Efficient techniques are developed for the computation of helicopter rotor tip vortex geometry and helicopter rotor harmonic airloads. These techniques are designed to minimize the computational expense by the use of simplified wake models together with other devices which reduce the amount of integration over the wake of the Biot Savart relation for induced velocity. These techniques are designed for use in steady-state flight at advance ratios below 0.3; however, they could be readily extended to higher advance ratios and to transient flight conditions. The results of the tip vortex geometry computations show that, over the forward portion of the rotor, the tip vortex is much closer to the rotor than the classical rigid wake assumption would indicate. This results in very intense, close blade-tip vortex interactions. These interactions must be modeled much more carefully than the less intense ones which occur when the rigid wake geometry assumption is used. The use of a lifting-surface solution for the airloads induced by these close blade-tip vortex interactions resulted in a substantial improvement in the agreement with measured airloads. Further improvement was obtained using a very simplified model for tip vortex-core bursting and for the propagation of that bursting ahead of the blade which initiated it. This, together with the lifting-surface solution, brought the computed airloads into reasonable agreement with the measured airloads. A simple tip vortex roll-up model was used to test the effect of roll-up on the airloads computation and it was found to be significant in some cases. The effects of tangentially-induced velocity and local separation on airloads computations were also evaluated and found to be of limited importance. It is recommended that close blade-vortex interactions and tip vortex formation and roll-up be studied both experimentally and theoretically. The currently available knowledge of these phenomena is inadequate for accurate harmonic airloads computations.

Sechaud, J.-F., Wolf, S. W. D., Carraz, G., Raynal, J.-C., Godard, J.-L., Bailly, D. and Coton, P.

"WAKE SURVEY TECHNIQUES IN THE ONERA INDUSTRIAL WIND TUNNELS"

AIAA Paper No. 2002-2923, St. Louis, MO, June 2002

ONERA is currently pursuing both near-field and far-field wake survey techniques to better understand the components of aircraft drag, and how the wake of an aircraft persists in the atmosphere. Within the frame of national French research programs, ONERA has recently improved and validated its experimental techniques for near-field wake surveys in its industrial wind tunnels: the F1 low-speed wind tunnel; the SZMA transonic wind tunnel; and the large SIMA high-speed wind tunnel. Some of the different tests performed to validate these near-field techniques are presented. These wake survey techniques provide detailed descriptions of the flow downstream of the models under investigation. The drag can then be broken down into its basic terms (viscous, wave and induced drag), and the local sources of drag visualized. For far-field wake surveys, our catapult facilities at Lille are used for free-flight model tests. These test techniques rely on non-intrusive measurement techniques to study the propagation of a model's wake up to 80 wing spans downstream. We believe these wake survey techniques will be of great help in the understanding and analysis of local flow phenomena and wakes which will lead to better aircraft designs to minimize drag and more efficient air traffic procedures.

Sedin, Y. C.-J., Grasjo, I., Kullberg, E. and Larsson, R.

"A MODEL FOR SIMULATION OF FLIGHT PASSAGES THROUGH TRAILING TIP VORTICES"

ICAS-2002-7.9.3, Toronto, Canada, September 2002

A model for simulation of flight in a vortex wake was developed. The model was demonstrated in desktop and in real time simulations with pilot and active flight control system. The model wake consists of two vortices. The induced computed aero database is superimposed on top the ordinary for simulations. The paper describes the model and shows some results.

Seelhorst, U., Beesten, B. M. J. and Butefisch, K. A.

"FLOW FIELD INVESTIGATION OF A ROTATING HELICOPTER ROTOR BLADE BY THREE-COMPONENT LASER-DOPPLER-VELOCIMETRY"

Aerodynamics and Aeroacoustics of Rotorcraft, AGARD-CP-552, August 1995, pp. 23-1 to 23-12.

The measurement of three-dimensional local flow vectors of a blade tip vortex at positions near the helicopter rotor plane were performed with a three-component laser-Doppler-velocimeter (3D LDV). A 'position monitoring system' synchronized to the blade rotation gave access to blade motion parameters like lead-lag and pitching at the desired radial position of the blade. Mainly results concerning the structure of blade tip vortices were obtained. The measurements of a vortex generated at hover condition showed the correctness of 'time history' data acquisition, e.g. taking data during the time interval when one blade is passing the location of the measuring volume of the LDV. Vortex

structure measurements at two different blade tips, a regular square tip for reference and a non-planer tip called winglet, were carried out. First of all, the influence of the winglets on vortex structure and blade vortex interaction (BVI) has been investigated. Then in addition to the vortex parameters like vortex/blade miss distance, vortex core size, axial velocity deficit, vortex strength, and vorticity distribution with respect to the spatial orientation of the vortex axis, results on 3D-vorticity distribution and the temporal vortex roll up for the different blade tip vortices have been obtained.

Segalini, A. and Alfredsson, P. H.

"A SIMPLIFIED VORTEX MODEL OF PROPELLER AND WIND-TURBINE WAKES"

Journal of Fluid Mechanics, Vol. 725, 2013, pp. 91-116.

A new vortex model of inviscid propeller and wind-turbine wakes is proposed based on an asymptotic expansion of the Biot-Savart induction law to account for the finite vortex core size. The circulation along the blade is assumed to be constant from the blade root to the tip approximating a turbine with maximum power production for given operating conditions. The model iteratively calculates the tip-vortex path, allowing the wake to expand/contract freely, and is afterward able to evaluate the velocity field in the whole domain. The 'roller-bearing analogy', proposed by Okulov and Sorensen, is used to determine the vortex core size. A comparison of the main outcomes of the present model with the general momentum theory is performed in terms of the operating parameters (namely the number of blades, the tip-speed ratio, the blade circulation, and the vortex core size), demonstrating good agreement between the two. Furthermore, experimental data have been compared with the model outputs to validate the model under real operating conditions.

Segalini, A., Orlu, R. and Alfredsson, P. H.

"UNCERTAINTY ANALYSIS OF THE VON KARMAN CONSTANT"

Experiments in Fluids, Vol. 11, 2013, pp. 1460-1468.

In 1930, von Karman presented an expression for the mean velocity distribution in channel and pipe flows that can be transformed into the today well-known logarithmic velocity distribution. At the same time, he also formulated the logarithmic skin friction law and obtained a value of 0.38 for the constant named after him through pipe flow pressure drop measurements. Different approaches to determine the von Karman constant from mean velocity measurements have been proposed over the last decades, sometimes giving different results even when employed on the same data, partly because the range over which the logarithmic law should be fitted is also under debate. Up to today, the research community has not been able to converge toward a single value and the favored values range between 0.36 and 0.44 for different research groups and canonical flow cases. The present paper discusses some pitfalls and error sources of commonly employed estimation methods and shows, using boundary layer data from Osterlund (1999) that von Karman's original suggestion of 0.38 seems to be valid for zero pressure gradient turbulent boundary layer flows. More importantly, it is shown that the uncertainty in

the determination of the von Karman constant can never be less than the uncertainty in the friction velocity, thereby yielding a realistic uncertainty for the most debated constant in wall turbulence.

Seiner, J. M., Ponton, M. K., Jansen, B. J., Dash, S. M. and Kenakowski, D. C.

"INSTALLATION EFFECTS ON HIGH SPEED PLUME EVOLUTION"

1997 ASME Fluids Engineering Division Summer Meeting, June 1997

An experimental and numerical study was conducted to examine the effect of the wing-tip vortex, wing wake, pylon wake, and angle-of-attack on the spatial distortion of an evolving high speed subsonic jet plume. One objective of the study was to evaluate the effect of this distortion on the radiated sound field. A generic powered nacelle was mounted with a generic pylon to a NACA 0012 airfoil. Both conventional probes and a planar laser light sheet were used to track the geometric center of the jet plume and wing-tip vortex. A cold resistance fine wire was used to measure total temperature fluctuations. Both the CRAFT and TTJET code were used for numerical simulations. Comparisons between experimental and numerical simulations were found to be in good agreement. Two supersonic rectangular nozzles, with aspect ratios of 1.56 and 2.0 were used to assess the non-azimuthal noise field. These convergent-divergent nozzles were designed for an exhaust Mach number of 1.5. The non-azimuthal sound field of the rectangular nozzles suggested, based on distortion of the installed plume flow field, that both angle-of-attack and wing tip vortex could lead to non-symmetric sound radiation for conventional aircraft at take-off.

Seliga, T. A. and Hazen, D. A.

"EVALUATION OF WIND ALGORITHMS FOR REPORTING WIND SPEED AND GUST FOR USE IN AIR TRAFFIC CONTROL TOWERS"

AMS 12th Conference on Aviation Range and Aerospace Meteorology, January - February, 2006, Atlanta, GA.

This paper examined several simple methods of evaluating short-term wind direction shift prediction, focusing on 2-min forward values derived from backward wind direction data. The results suggest that 2-min BW averaging for average wind direction and 10-min BW look-backs for wind range are reasonable standards for aviation reporting. The data provide evidence that 5-min BW averaging and look backs for both parameters may be optimum. The wind direction range was found to correlate with wind direction standard deviation, like results of Markee (1963) who analyzed wind data over 15-min, 30-min and 60-min time intervals. The findings here also agreed with his results that showed that the wind direction range is not correlated with wind speed standard deviation (not a good predictor). These limited results show that, irrespective of the many studies of winds that have been performed previously, much remains to be learned. In particular, more sophisticated approaches to analyzing winds should improve predictions, reducing both missed reports and false reports. Essentially, current methods may be considered naive compared to state-of-art time series and statistical analysis methods, including such topics as: time series filtering; neural networks; and fuzzy logic modeling.

Seliga, T. A. and Mead, J. B.

"METER-SCALE OBSERVATIONS OF AIRCRAFT WAKE VORTICES IN PRECIPITATION USING A HIGH RESOLUTION SOLID-STATE W-BAND RADAR"

AMS 34th Conference on Radar Meteorology, Paper 10.25, October 2009, Williamsburg, VA.

Detection, tracking and characterization of wake vortices generated by aircraft during takeoff and landing are important to assess threats to aviation safety and ensuring that air traffic control procedures adequately account for the phenomenon. This paper reports on a radar technology that may provide valuable contributions to these efforts. Specifically, meter-scale detection of aircraft wake vortices in light rain has been demonstrated using a low power (100 mW), solid-state W-Band (94 GHz) radar system. The radar employs a 1.2 m diameter antenna on a scanning pedestal, providing a 1.5-m 6-dB cross track beam pattern at 500-m range. Range resolution as fine as 1.0-m is achieved using stretch processing, which also provides processing gain on the order of 30 dB. Additional coherent gain is achieved through FFT processing at each range gate. Range sidelobe suppression of greater than 40 dB makes this system suitable for high spatial and temporal resolution meteorological research such as the investigation of wake turbulence behavior during aircraft takeoff and landing operations.

Sellier, B. and Pigere, J.

"LASER DOPPLER ANEMOMETRY STUDY OF HELICOPTER ROTOR WAKE AIRFLOW"

International Symposium on Applications of Laser-Doppler Anemometry to Fluid Mechanics, Lisbon, July 1982

The equipment, instrumentation, and results of a laser Doppler anemometry study of helicopter rotor wake airflow are described. Azimuthal and radial distributions of vertical induced velocities and tip vortex paths are determined for the cases of hovering and forward flight. Attention is given to the arrangement of the laser velocimeter system and the data acquisition system, which can operate in both a 'wake' and a 'histogram' mode. The former simultaneously obtains the two induced velocities and the angular position of the blade, while the latter, velocities are measured for one given azimuthal blade location.

Selvam, R. P. and Millet, P. C.

"COMPUTER MODELING OF TORNADO FORCES ON A CUBIC BUILDING USING LARGE EDDY SIMULATION"

Journal of the Arkansas Academy of Science, Vol. 57, 2003, pp. 140-146.

A tornado changes its wind speed and direction rapidly; therefore, it is difficult to study the effects of a tornado on buildings in a wind tunnel. The status of the tornado-structure interaction and various models of the tornado wind field found in literature are surveyed. Three-dimensional computer

modeling work using the turbulence model based on large eddy simulation is presented. The effect of a tornado on a cubic building is considered for this study. The Navier-Stokes (NS) equations are approximated by the finite difference method and solved by an implicit procedure. The force coefficients are plotted in time to study the effect of Rankine combined vortex model. The tornado is made to translate at a 0- and 45-degree angle, and the grid resolution is refined. Some flow visualizations are also reported to enhance understanding of the flow behavior around the cube.

Sen, R.

"VORTEX-OSCILLATION MODEL OF AIRFOIL SIDE-EDGE NOISE"

AIAA Journal, Vol. 35, No. 3, March 1997, pp. 441-449

Oscillation of the edge vortex is proposed as a mechanism for sound production at the lateral edge of a loaded airfoil. Flow in a spanwise cross section near the edge is idealized by potential flow around a square corner, and the time-averaged edge vorticity is represented by a single line vortex perpendicular to the plane of the flow. Based on a stability requirement, we calculate vortex oscillation modes with frequencies dependent on circulation, edge thickness, and mean distance from the edge. Realistic numbers for these parameters give frequencies that are consistent with measured noise and surface pressure frequencies. Reasonable surface pressure amplitudes are also predicted when experimental estimates of vortex oscillation amplitude are used. Interaction with large flow structures is simulated by perturbing the base vortex with a smaller vortex. This produces pressure spectra with broad peaks, as observed in experiments. The mechanism for broadening is nonlinear dynamics with transition to chaos. Far-field pressure is governed by the speed at which the center of vorticity moves normal to the wall. This previously obtained result is explained by a simple image argument. In a single-vortex model of the edge vorticity, noise production may be reduced by moving the equilibrium position far from the wall; this suppresses the normal component of the vortex-oscillation eigenvector. In multiple-vortex models, noise production may be suppressed by promoting antisymmetric motion. This occurs when the edge-vorticity field is compact or is positioned far from the wall.

Send, W.

"DOWNSTREAM VORTICITY MEASUREMENTS FROM ULTRASONIC PULSES"

J. Aircraft, Vol. 25, No. 11, November 1988, pp. 993-994

The vorticity distribution behind a profile is obtained from the measurement of the running-time shift, which an ultrasonic pulse experiences in wind tunnel flow. The spatial gradient of the running-time shift is related to the vorticity vector. The method is limited by the assumptions of incompressible flow and a high Reynolds number.

Serakawi, A. R. and Ahmad, K. A.

"EXPERIMENTAL STUDY OF HALF-DELTA WING VORTEX GENERATOR FOR FLOW SEPARATION CONTROL"

Journal of Aircraft, Vol. 49, No. 1, January-February 2012, pp. 76-81.

This paper describes an experimental study of the effects of passive half-delta wing vortex generators on a backward-facing ramp flow. Four models of vortex generators with aspect ratios of 0.4, 0.8, and 1.6 were tested in an open-circuit wind tunnel. The vortex generators were placed upstream of the backward-facing ramp where their heights were 24 and 48 percent of the boundary-layer thickness. Flow visualization and velocity measurements were conducted using a particle image velocimetry system. The results showed that an array of vortex generators with an aspect ratio of 1.6 had the highest efficiency in reducing the flow separation region.

Sereno, J. L. and Pereira, J. C. F.

"UNCERTAINTY QUANTIFICATION OF TWO-DIMENSIONAL WAKE VORTICES NEAR THE GROUND"

Journal of Aircraft, Vol. 49, No. 4, July-August 2012, pp. 1175-1178.

The objective of this work is to study the stochastic two-dimensional interaction of a vortex pair with a wall, under crosswind, considering different uncertainty sources: 1) vortex Reynolds number (circulation), 2) position of the vortices relative to each other, and 3) crosswind velocity. The stochastic solutions were obtained recurring to the polynomial chaos expansion method of random processes applied to the 2-D unsteady Navier-Stokes equations. The method quantifies the extent, dependence, and propagation of uncertainty through the model system, and particularly a methodology for the calculation of the vortex-trajectory variability (i.e., the confidence interval) could be obtained, provided that the randomness of the inputs is not sufficiently high to destroy the ensemble mean solution coherence.

Serrano-Aguilera, J. J., Garcia-Ortiz, J. H., Gallardo-Claros, A., Parras, L. and del Pino, C.

"EXPERIMENTAL CHARACTERIZATION OF WINGTIP VORTICES IN THE NEAR FIELD USING SMOKE FLOW VISUALIZATIONS"

Experiments in Fluids, Vol. 57, 2016, pp. 137-1 to 137-11.

In order to predict the axial development of the wingtip vortices strength, an accurate theoretical model is required. Several experimental techniques have been used to that end, e.g. PIV or hot-wire anemometry, but they imply a significant cost and effort. For this reason, we have performed experiments using the smoke-wire technique to visualize smoke streaks in six planes perpendicular to the main stream flow direction. Using this visualization technique, we obtained quantitative information regarding the vortex velocity field by means of Batchelor's model for two chord-based Reynolds numbers, $Re = 33,300$ and $100,000$. Therefore, this theoretical vortex model has been introduced in the integration of ordinary differential equations which describe the temporal evolution of streak lines as function of two parameters: the swirl number, S , and the virtual axial origin, z_{sub-0} . We have applied two different procedures to minimize the distance between experimental and theoretical flow patterns: individual curve fitting at six different control planes in the streamwise direction and the global curve fitting which corresponds to all the control planes simultaneously. Both

sets of results have been compared with those provided by del Pino et al. (Phys Fluids 23(013):602, 2001b. doi:10.1063/1.3537791), finding good agreement. Finally, we have observed a weak influence of the Reynolds number on the values S and z_0 at low-to-moderate Re . The experimental technique is proposed as a low-cost alternative to characterize wingtip vortices based on flow visualization.

Serre, E. and Bontoux, P.

"VORTEX BREAKDOWN IN A THREE-DIMENSIONAL SWIRLING FLOW"

Journal of Fluid Mechanics, Vol. 459, 2002, pp. 347-370.

Time-dependent swirling flows inside an enclosed cylindrical rotor-stator cavity with aspect ratio $H/R = 4$, larger than the ones usually considered in the literature, are studied. Within a certain range of governing parameters, vortex breakdown phenomena can arise along the axis. Very recent papers exhibiting some three-dimensional effects have simulated new interest in this topic. The study is carried out by a numerical resolution of the three-dimensional Navier-Stokes equations, based on high-order spectral approximations to ensure very high accuracy of the solutions. The first transition to an oscillatory regime occurs through an axisymmetric bifurcation (a supercritical Hopf bifurcation) at $Re = 3500$. The oscillatory regime is caused by an axisymmetric mode of centrifugal instability of the vertical boundary layer and the vortex breakdown is axisymmetric, being composed of two stationary bubbles. For Reynolds numbers up to $Re = 3500$, different three-dimensional solutions are identified. At $Re = 4000$, the flow supports the $k = 5$ mode of centrifugal instability. By increasing the rotation speed to $Re = 4500$, the vortex breakdown evolves to an S-shaped type after a long computational time. The structure is asymmetric and gyrates around the axis inducing a new time-dependent regime. At $Re = 5500$, the structure of the vortex breakdown is more complex: the upper part of the structure takes a spiral form. The maximum rotation speed is reached at $Re = 10000$ and the flow behavior is now chaotic. The upper structure of the breakdown can be related to the spiral-type. Asymmetric flow separation on the container wall in the form of spiral arms of different angles is also prominent.

Settles, G. S. and Cattafesta III, L. N.

"SUPERSONIC SHOCK WAVE/VORTEX INTERACTION"

NASA-CR-192209, Sept. 1991, Penn State University, University Park, PA.

The shock/vortex interaction is a basic and important fluid mechanics problem. Vortices are susceptible to bursting or breakdown when they encounter regions of high adverse pressure gradient. In supersonic flows, such a phenomenon can occur when vortices shed from delta wings of vehicles flying at high angles of attack interact with shock waves generated by the vehicle. In addition, vortices ingested into engine inlets may interact with the inlet shock system and adversely affect engine performance. However, very little research has been conducted on the topic of shock/vortex interaction. In one study, NASA Ames/Penn State University Consortium Agreement NCA2-235, the possibility of generating, controlling, and measuring supersonic streamwise vortices was confirmed.

This study also began to elucidate the phenomenology of the shock/vortex interaction. This research has continued over the last two years. The goals of the program are: to determine the structure of supersonic, streamwise, turbulent vortices; to thoroughly explore the phenomenology of the shock/vortex interaction; to determine the limits for the onset of supersonic vortex breakdown; to characterize the unsteadiness of the shock/vortex interaction; and to make detailed measurements of the interaction flowfield. Research activities of the past year have focused on mean flow measurements of the vortices and flow visualization experiments designed both to explore shock/vortex interactions and to determine the conditions for the onset of vortex breakdown. The results of the study should be of value in assessing the effect of shock/vortex interactions on high-speed flight and propulsion. Their immediate use will likely be in code validation exercises to test NASA-Ames' computational ability to model such complex turbulent flows. Our primary goal, of course, is to contribute new and fundamental knowledge in the field of high-speed fluid dynamics.

Sevil, H. E.

"AIRDATA SENSOR BASED POSITION ESTIMATION AND FAULT DIAGNOSIS IN AERIAL REFUELING"

PhD Thesis, August 2013, University of Texas, Arlington, TX.

Aerial refueling is the process of transferring fuel from one aircraft (the tanker) to another (the receiver) during flight. In aerial refueling operations, the receiver aircraft is exposed to a nonuniform wind field induced by the tanker aircraft, and this nonuniform wind field leads to differences in readings of air data sensors placed at different locations on the receiver aircraft. There are advantages and disadvantages of this phenomenon. As an advantage, it is used as a mechanism to estimate relative position of the receiver aircraft inside the nonuniform wind field behind the tanker. A model of the nonuniform wind field is used to construct maps of the wind field as functions of relative position in terms of airspeed, side slip angle and angle of attack. Several algorithms are developed that use measurements from three air data sensors placed at different locations on the receiver aircraft and the inverse of the maps to estimate the relative position of the receiver with respect to the tanker. The disadvantage of the phenomenon is that the differences in the readings of air data sensors cause false fault detections in a redundant-sensor-based Fault Detection and Isolation (FDI) system developed based on the assumption of identical sensor readings from three air data sensors. Such an FDI algorithm successfully performs detection and isolation of sensor faults when the receiver aircraft flies solo or outside the wake of the tanker aircraft. However, the FDI algorithm yields false fault detection when the receiver aircraft enters the tanker's wake. This problem is resolved by modifying the FDI algorithm. For robustness, the expected values of the sensor measurements are incorporated in the FDI algorithm, instead of the assumption of identical measurements from the sensors. The expected values, which depend on the position of the receiver relative to the tanker, are obtained from the maps of the nonuniform wind field as functions of the relative position. The new robust FDI detects and isolates sensor faults, as well as it eliminates the false fault detection in the nonuniform wind field induced by the tanker aircraft.

Sevil, H. R. and Dogan, A.

"FAULT DIAGNOSIS IN AIR DATA SENSORS FOR RECEIVER AIRCRAFT IN AERIAL REFUELING"

Journal of Guidance, Control, and Dynamics, Vol. 38, No. 10, October 2015, pp. 1959-1975.

Multiple air-data sensors placed on different positions on an aircraft are usually expected to provide identical measurements. This is because aircraft are assumed to fly in no-wind or uniform wind conditions. There are cases, however, where an aircraft flies in nonuniform wind vector field with significant variations in magnitude and direction over the dimensions of the aircraft. For example, in an aerial refueling operation, the receiver aircraft needs to fly within the nonuniform wind field induced by the wake of the tanker aircraft. This paper shows that an air-data sensor fault detection and isolation algorithm, if developed with an underlying assumption of identical sensor measurements, yields very high false detection rate when the aircraft enters the wake of another aircraft. This paper also presents a novel modification in the redundant-sensor-based fault detection and isolation algorithm that eliminates this problem. The new method is based on a model of the wind field as a function of relative position with respect to the tanker aircraft. This model is used to compute the expected values of air-data sensor measurements given the position of the receiver aircraft relative to the tanker.

Sezer-Uzol, N.

"HIGH-ACCURACY WAKE AND VORTEX SIMULATIONS USING A HYBRID EULER/DISCRETE VORTEX METHOD"

MS Thesis, May 2001, Dept. Aerospace Engineering, Penn State University, University Park, PA.

A new approach has been developed which preserves vortices over long distances. This new hybrid Computational Fluid Dynamics / Discrete Vortex (CFD/DV) method couples a Lifting-Line/Free-Wake method with an unstructured grid, parallel 3-D finite volume CFD flow solver. The total solution field is separated into two parts: the potential flow field from the DV solution and the deviation from this DV flow field. The modified Euler equations for the hybrid CFD/DV method are then solved and the total solution field is obtained. The tip vortex and wake of a fixed rectangular wing is investigated as a test case. Comparison of the wing surface pressure distributions to the available experimental data showed good agreement. The results obtained with the hybrid method are compared to those without the hybrid method. Simulation of the experiments done by Davenport et al., which have measurements on the vortex structure up to 30 chord lengths downstream, showed encouraging results. It is expected to preserve the tip vortex shed from the wing tip over longer distances when the hybrid CFD/DV method is applied. The wing tip vortex is quickly dissipated due to numerical diffusion in solutions without the hybrid method.

Sforza, P. M.

"SHOCK-VORTEX INTERACTION RESEARCH"

RTO-EN-4, November 1998, Research and Technology Organization, Neuilly-Sur-Seine, France

Supersonic cruise aircraft generate shock waves and vortices because of the flight speed and the forces generated, respectively. Interactions between these two produce flow disturbances which affect aircraft performance, stability, and control. Research in the field is reviewed to provide an understanding of the state of the art. The important parameters in the interaction are the Mach number and the swirl to axial velocity ratio of the vortex. The phenomenon of vortex breakdown is described and a criterion for determining if a shock-vortex interaction is strong enough to provoke it is given. Models developed thus far for evaluating such interactions are presented. Experimental investigations of shock-vortex interactions are also discussed.

Sforza, P. M.

"VORTEX-PLUME INTERACTION RESEARCH"

RTO EN-4, May 1998 RTO AVT, Rhode-Saint-Genese, Belgium, May 1998

The problem of the wake of an aircraft cruising at supersonic speed in the stratosphere is presented. The two major components of the flow field are the trailing vortex wake and the jet exhaust plumes. Accurate prediction of the dispersion of engine emissions resulting from interaction between the two has important consequences for determination of wake signatures. Research in the field is reviewed to provide an understanding of the present state of the art. Synthesis of these different jet and vortex studies provides a unified global description of aircraft wakes in terms of a length scale bA/CL , based on the span, aspect ratio, and cruise lift coefficient. A model is developed in which the jet plumes, being immersed in the trailing vortex wake downwash, are assumed to deform into twin vortices typical of jets in a cross-flow. This permits the development of the wake flow field to be assessed with the relatively simple tools of vortex filament analysis. Wakes of both conventional high subsonic and supersonic aircraft may be accommodated by this approach, as would the wakes of wing-jet combination injectors for scramjet applications. Experimental studies that would aid in the development of more accurate prediction methods are also described.

Sforza, P. M.

"AIRCRAFT VORTICES: BENIGN OR BALEFUL?"

Space/Aeronautics, April 1970, pp. 42-48

Vortices in aerodynamics are discussed with application to aircraft. The use of vortex lattice calculation techniques are described as are the effect of leading-edge vortices on the lift of low aspect ratio wings. Fuselage and wing tip vortices are shown to have a strong effect on stability and control of the generating aircraft as well as other aircraft operating in its wake.

Sforza, P. M.

"CIRCULATION DISTRIBUTION IN LEADING EDGE VORTICES"

AIAA Paper No. 2005-5161, June 2005, Toronto, Canada.

Data from a variety of experiments on leading edge vortices over sharp-edged delta wings are used to formulate an expression for the circulation distribution. A logarithmic region is shown to provide a transition between an exponential distribution in the viscous core and the spiral vortex outer flow. Pohlhamus's circulation function for the attached flow lift is found to scale the observed circulation characteristics in the primary vortex over the delta wing.

Sforza, P. M.

"ENTRAINMENT IN LEADING-EDGE AND TRAILING VORTICES"

AIAA Paper No. 2007-4362, Miami, FL, June 2007

Leading edge vortices from delta wings and trailing vortices from wings in general may be characterized as orderly vortex flows aligned with a mainstream flow. The nature of the axial flow in the core of the vortex determines the nature of the entrainment produced by the vortex. Jet-like, wake-like, or constant axial velocity distributions in the core of the vortex result in greatly differing entrainment characteristics. The mass entrainment by the vortex and its relationship to the variation of the axial flow in the vortex according to the continuity equation is described. It is shown that conventional trailing vortices do not entrain mass but rather diffuse into the constant outer flow while leading edge vortices have substantial entrainment properties. Then further analysis of the vortex according to momentum conservation illustrates the dependence of the entrainment on the circulation in the leading-edge vortex. Finally, the mass entrainment is related to the aerodynamic characteristics of the generating delta wing.

Sforza, P. M.

"INTERACTION OF WING VORTICES AND PLUMES IN SUPERSONIC FLIGHT"

IUTAM Symposium on Dynamics of Slender Vortices, Aachen, Germany, August 31-September 3, 1997

A model of the wake of an aircraft cruising at high speed in the stratosphere is presented. The two major components of the flow field are the trailing vortex wake and the jet exhaust plumes. The prospect of large fleets of supersonic airliners makes it important to accurately predict the dispersion of engine emissions resulting from interaction between the two. Here, synthesis of several different jet and vortex studies provides a unified description of aircraft wakes in terms of a length scale bA/CL , based on the span, aspect ratio, and cruise lift coefficient. The basic premise of the model is that jet plumes, being immersed in the trailing vortex wake downwash, deform into twin vortices typical of jets in a cross-flow. This permits the development of the wake flow field to be assessed with the tools of vortex filament analysis. The wakes of both conventional high subsonic and supersonic aircraft are shown to be accommodated by this approach, as would the wakes of wing-jet combination injectors for scramjet applications. Experimental studies which would aid in the development of more accurate prediction methods are also described.

Sforza, P. M. and Smorto, M. J.

"STREAMWISE DEVELOPMENT OF THE FLOW OVER A DELTA WING"

AIAA Paper No. 1980-0200, January 1980, Pasadena, CA.

An experimental investigation of the low-speed flow over a highly swept delta wing with sharp leading edges is presented. Velocity measurements in the separated leading-edge vortex which dominates the three-dimensional flow field are shown for several different chordwise stations, and serve to illustrate the streamwise development of the vortex. This data is also used to determine the trajectory of the vortex over the delta and to calculate the circulation distribution in the flow, and these results are compared to those of previous studies.

Sforza, P. M. and Smorto, M. J.

"STREAMWISE DEVELOPMENT OF THE FLOW OVER A DELTA WING"

AIAA Journal, Vol. 19, No. 7, July 1981, pp. 833-834.

An experimental investigation of the low-speed flow over a highly swept delta wing with sharp leading edges and at high angle of attack is presented. Velocity measurements in the separated leading-edge vortex are shown for several different chordwise stations, and serve to illustrate the streamwise development of the vortex. From these measurements the total vortex circulation has been calculated and is shown to compare well to that obtained theoretically by Polhamus. It is found that the vortex flowfield does not exhibit axisymmetry nor does it scale linearly with the half-span; a contradiction of two widely used assumptions in previous theoretical analyses. In the region of the axis of rotation, the viscous character of the flow becomes important and the core is found to grow linearly with downstream distance, while the maximum velocity is found to decrease with downstream distance.

Sforza, P. M., Sheerin, P. and Smorto, M.

"THREE-DIMENSIONAL WAKES OF SIMULATED WIND TURBINES"

AIAA Journal, Vol. 19, No. 9, September 1981, pp. 1101-1107.

An experimental and theoretical investigation of the wake behind a porous disk which simulates the effect of a wind turbine is presented. Modeling of the wake in an environmental wind tunnel is described and experimental results for the three-dimensional model wake flowfield are presented. A three-dimensional turbulent flow analysis is developed to deal with prediction of the wake characteristics. The theoretical results are shown to display the experimentally observed features of the wake.

Sforza, P. M., Stasi, W. and Gotkin, L.

"AN EXPERIMENTAL FACILITY FOR WIND ENGINEERING RESEARCH"

AIAA Paper No. 1978-813, April 1978, San Diego, CA.

Experimental research in wind engineering must rely on testing in a controlled laboratory environment as well as field testing in the uncontrolled natural wind. A facility for such research, developed in the Aerodynamics Laboratories of the Polytechnic Institute of New York, is described. This facility includes both a field test station and a laboratory test station for atmospheric boundary layer research. The utilization of this complex is discussed in terms of an ongoing project on wind energy conversion to illustrate the various capabilities that have been developed. Application of this facility to other problems in wind engineering are also described.

Sforza, P. M., Stasi, W., Pazienza, J. and Smorto, M.

"FLOW MEASUREMENTS IN LEADING EDGE VORTICES"

AIAA Paper No. 77-11, Los Angeles, CA, January 1977.

An experimental study of the vortex flow field over slender delta planforms with sharp leading edges is presented. Complete velocity measurements in this three-dimensional flow field are obtained by means of a Conrad type probe used in conjunction with a five-degree-of-freedom traversing mechanism and flow visualization is achieved by an oil fog technique. Effects of angle of attack, camber, sweepback, etc, are described. A new application of such flows, that of wind energy conversion by means of the Vortex Augmentor Concept developed by the first author, is discussed.

Sforza, P. M., Stasi, W., Smorto, M. and Sheerin, P.

"WIND TURBINE GENERATOR WAKES"

AIAA Paper No. 1979-0113, January 1979, New Orleans, LA.

An experimental and theoretical investigation of the wake behind wind turbine generators is presented. The general features of such flows are reviewed and the applicability of past work on more conventional aerodynamic wakes is discussed. Modeling of the wind turbine and the atmospheric boundary layer in an environmental tunnel is described. Experimental results for such models are given. Theoretical modeling of the three-dimensional mixing process in the wake-boundary layer interaction region is performed and numerical solutions for such flows are discussed and compared to the experiments.

Shadden, S. C., Katija, K., Rosenfeld, M., Marsden, J. E. and Dabiri, J. O.

"TRANSPORT AND STIRRING INDUCED BY VORTEX FORMATION"

J. Fluid Mech., Vol. 593, 2007, pp. 315-331

The purpose of this study is to analyze the transport and stirring of fluid that occurs owing to the formation and growth of a laminar vortex ring. Experimental data was collected upstream and downstream of the exit plane of a piston-cylinder apparatus by particle-image velocimetry. This data was used to compute Lagrangian coherent structures to demonstrate how fluid is advected during the transient process of vortex ring formation. Similar computations were performed from computational fluid dynamics (CFD) data, which showed qualitative agreement with the experimental results, although the CFD data provides better resolution in the boundary layer of the cylinder. A parametric study is performed to demonstrate how varying the piston-stroke length-to-diameter ratio affects fluid entrainment during formation. Additionally, we study how regions of fluid are stirred together during vortex formation to help establish a quantitative understanding of the role of vortical flows in mixing. We show that identification of the flow geometry during vortex formation can aid in the determination of efficient stirring. We compare this framework with a traditional stirring metric and show that the framework presented in this paper is better suited for understanding stirring/mixing in transient flow problems. A movie is available with the online version of the paper.

Shah, P. N., Atsavapranee, P., Hsu, T. Y., Wei, T. and McHugh, J.

"TURBULENT TRANSPORT IN THE CORE OF A TRAILING HALF-DELTA-WING VORTEX"

Journal of Fluid Mechanics, Vol. 387, 1999, pp. 151-175.

The development of a turbulent streamwise vortex core in the wake of a half delta wing has been examined using high-resolution DPIV. The objective of this work was to gain understanding of the transport processes at work a short distance downstream of the wing trailing edge as the wake vortex developed. Experiments were conducted in the Rutgers Free Surface Water Tunnel using an in-house DPIV system. A turbulent streamwise vortex was generated by a half delta wing, with 44 cm chord length and 60-degree sweep angle, mounted at 30 degrees angle of attack. Reynolds number based on chord length was 65,000. Laser sheets oriented perpendicular to the flow direction were positioned 1, 3.5, and 7 chord lengths downstream of the wing trailing edge. Instantaneous vortex centers were identified to track vortex meandering as well as for better quantification of turbulence levels in the vortex core. Mean and fluctuating turbulence terms in the mean streamwise vorticity transport equation along with turbulent kinetic energy dissipation and production were evaluated relative to an inertial reference frame as well as relative to a vortex-centered frame. The results of this analysis highlight the importance of this near-wake region to the downstream evolution of the trailing vortices. There is a high degree of dissipation as well as streamwise vorticity convection in the near wake which increases rapidly with increasing distance from the trailing edge.

Shaidakov, V. I.

"INDUCTIVE PROPERTIES OF BENT VORTEX CORDS AND THEIR APPLICATION TO CONSTRUCTING A MODEL OF WAKE VORTEX HELICOPTER ROTOR"

Civil Aviation High Technologies, No. 223, 2016, pp. 84-92.

This article provides information about the properties of BENT inductive vortices capable of under the influence of self-induction to move at a speed independent of circulating gamma, the size of the nucleus and the local curvature of the individual sections of vortex tube. For numerical calculations the method of accounting for the self-induction at the nodal point of the vortex tube segments is provided. Formulas and recommendations for the construction of models of the free-vortex wake in the rotor blade theory is provided. [In Russian.]

Shamroth, S. J. and Briley, W. R.

"A VISCOUS FLOW ANALYSIS FOR THE TIP VORTEX GENERATION PROCESS"

NASA CR-3184, October 1979, Scientific Research Associates, Inc., Glastonbury, CT.

A three-dimensional, forward-marching, viscous flow analysis is applied to the tip vortex generation problem. The equations include a streamwise momentum equation, a streamwise vorticity equation, a continuity equation, and a secondary flow stream function equation. The numerical method used combines a consistently split linearized scheme for parabolic equations with a scalar iterative ADI scheme for elliptic equations. The analysis is used to identify the source of the tip vortex generation process, as well as to obtain detailed flow results for a rectangular planform wing immersed in a high Reynolds number free stream at 6-degree incidence.

Shams, Q. A., Zuckerwar, A. J. and Knight, H. K.

"WAKE VORTEX AVOIDANCE SYSTEM AND METHOD"

US Patent 9,620,025 B2, April 2017.

A wake vortex avoidance system includes a microphone array configured to detect low frequency sounds. A signal processor determines a geometric mean coherence based on the detected low frequency sounds. A display displays wake vortices based on the determined geometric mean coherence.

Shan, H., Jiang, L. and Liu, C.

"DIRECT NUMERICAL SIMULATION OF FLOW SEPARATION AROUND A NACA 0012 AIRFOIL"

Computers and Fluids, Vol. 34, Issue 9, November 2005, pp. 1096-1114

Direct numerical simulation (DNS) for the flow separation and transition around a NACA 0012 airfoil with an attack angle of 4 degrees and Reynolds number of 100,000 based on free-stream velocity and chord length is presented. The details of the flow separation, detached shear layer, vortex shedding, breakdown to turbulence, and re-attachment of the boundary layer are captured in the simulation. Though no external disturbances are introduced, the self-excited vortex shedding and self-sustained

turbulent flow may be related to the backward effect of the disturbed flow on the separation region. The vortex shedding from the separated free shear layer is attributed to the Kelvin-Helmholtz instability.

Shankar, S. and Van Dommelen, L.

"A NEW DIFFUSION PROCEDURE FOR VORTEX METHODS"

Journal of Computational Physics, Vol. 127, 1996, pp. 88-109

A new method is proposed for simulating diffusion in vortex methods for two-dimensional incompressible flows. The method resolves length scales up to the spacing of the vortices. The grid-free nature of vortex methods is fully retained and the distribution of the vortices can be irregular. It is shown for the Stokes equations that in principle, the method can have any order of accuracy. It also conserves circulation, linear, and angular momentum. The method is based on exchanging a conserved quantity between arbitrary computational points. This suggests that extensions to more general flows may be possible. For the two-dimensional incompressible flows studied, circulation is exchanged between vortices to simulate diffusion. The amounts of circulation exchanged must satisfy a linear system of equations. Based on stability considerations, the exchanged amounts should further be positive. A procedure to find a solution to this problem is formulated using linear programming techniques. To test the method, the decay processes of a single point vortex and of a counterrotating pair of point vortices are computed. Current limitations of the method are discussed.

Shapiro, A. R.

"LASER PROPAGATION IN AIRCRAFT WAKES"

Proceedings SPIE, Vol. 2005, Optical Diagnostics in Fluid and Thermal Flow, December 1993, pp. 139-154.

The use of lasers aboard aircraft is affected by the perturbed airflow in its vicinity. Therefore, an ability to predict the structure of aircraft-induced turbulence would be useful in system and performance analysis. PSR performed temperature and velocity fluctuation measurements in the wakes of an NRA-3B and a B-1B at trail distances of 50 to 5500 m, at two Mach numbers (0.5 and 0.75) and at two altitudes (0.9 and 6 km). Preliminary analysis of the data suggested significant differences with the predictions of the computational fluid dynamics code (CFD) WAKE developed for this application by ARAP for U.S. Air Force. These differences impact laser propagation. The principal difference between the data and the CFD predictions is that the temperature fluctuations which determine C_{θ}^2 are not isotropic and exhibit spectra and correlation scales which differ greatly from those of velocity. This paper reports the development of a hypothesis concerning the source of this temperature structure in aircraft wakes. Modifications to CFD models are suggested.

Shapiro, A. R. and Churnside, J. H.

"HOT JET/WAKE TURBULENT STRUCTURE AND LASER PROPAGATION, PART 3: LASER PROPAGATION MEASUREMENTS AND MODELING"

21st JANNAF Exhaust Plume Technology Meeting, Vol. 1, Oct. 1994, pp. 79-95.

The use of lasers aboard aircraft is affected by the perturbed airflow in its vicinity. Therefore, an ability to predict the structure of aircraft-induced turbulence would be useful in system and performance analysis. We performed temperature and velocity fluctuation measurements in the wakes of an NRA-3B and a B-1B at trail distances of 50 to 5500 m, at two Mach numbers (0.5 and 0.75) and at two altitudes (0.9 and 6 km). Analysis of the data suggested significant differences with the predictions of the computational fluid dynamics code (CFD) WAKE developed for this application. The magnitude and scales of the temperature fluctuations suggest that first order laser propagation models would not apply. The principal difference between the data and the CFD predictions is that the temperature fluctuations which determine C_{θ}^2 are not isotropic and exhibit spectra and correlation scales which differ greatly from those of velocity. This paper reports wind tunnel measurements to determine the source of this temperature structure in aircraft wakes and laser propagation measurements in this regime. Modifications to CFD and to propagation models are suggested.

Shariff, K.

"MAKING AIRCRAFT VORTICES VISIBLE TO RADAR BY SPRAYING WATER INTO THE WAKE"

Journal of Atmospheric and Oceanic Technology, Vol. 33, December 2016, pp. 2615-2638.

Aircraft trailing vortices pose a danger to following aircraft during takeoff and landing. This necessitates spacing rules, based on aircraft type, to be enforced during approach in instrument flight regulation (IFR) conditions; this can limit airport capacity. To help choose aircraft spacing based on the actual location and strength of the wake, it is proposed that wake vortices can be detected using conventional ground-based precipitation and cloud radars. This is enabled by spraying a small quantity of water into the wake from near the wing. The vortex strength is revealed by the Doppler velocity of the droplets. In the present work, droplet size distributions produced by nozzles used for aerial spraying are considered. Droplet trajectory and evaporation in the flow field is numerically calculated for a heavy aircraft, followed by an evaluation of radar reflectivity at 6 nautical miles (n mi) behind the aircraft. Small droplets evaporate, while larger droplets fall out of the wake. In the humid conditions that typically prevail during IFR, enough droplets remain in the wake and give good signal-to-noise ratios (SNR). For conditions of average humidity, higher-frequency radars combined with spectral processing give good SNR.

Shariff, K. and Leonard, A.

"VORTEX RINGS"

Annual Review, Fluid Mechanics, Vol. 24, 1992, 235-279

Saffman (1981), in encapsulating the vortex ring problem, said that 'one particular motion exemplifies the whole range of problems of vortex motion and is also a commonly known phenomenon, namely, the vortex ring. Their formation is a problem of vortex sheet dynamics, the steady state is a problem of existence, their duration is a problem of stability, and if there are several we have a problem of vortex interactions.' We shall do our best to follow this paradigm in organizing this article but sometimes we are forced to make a division along viscous/inviscid lines. The next section focuses on the problem of formation by discussing how rings are generated naturally and, in the laboratory, their resulting structure, and finally, what factors determine whether the rings are laminar or turbulent. Section 3 describes three stages in the life of a laminar ring. Section 4 discusses inviscid dynamics and begins with a discussion of how core dynamics influences overall ring motion (Section 4.1). There are examples of laminar vortices in two dimensions, which attain a balance of nonlinear terms in the inner core; the suggestion that this may be also true of laminar rings is a thread that connects laminar rings to Section 4.2, which discusses the theory of inviscid steady-state rings. Largely however, this body of work stands apart. Unsteady inviscid effects such as mutual straining are discussed in Section 4.3. In describing how two rings interact along a common axis of symmetry, Section 5 is happily able to unite viscous with inviscid thinking, and experimental with numerical results. Three types of interactions are considered: 'leapfrogging' head-on collisions, and collisions with a no-slip wall. The subject of azimuthal instabilities is taken up in Section 6: The linear instability theory has been reasonably successful in accounting for experimental observation but later stages in the breakdown are not well understood. The last section discusses turbulent vortex rings and puffs.

Shariff, K. and Wray, A.

"ANALYSIS OF THE RADAR REFLECTIVITY OF AIRCRAFT VORTEX WAKES"

J. Fluid Mech., Vol. 463, 2002, pp. 121-161

Radar has been proposed as a way of tracking wake vortices to reduce aircraft spacing and tests have revealed radar echoes from aircraft wakes in clear air. The mechanism causing refractive index gradients in these tests is thought to be the same as that for homogeneous and isotropic atmospheric turbulence in the Kolmogorov inertial range, for which there is a scattering analysis due to Tatarski. However, the structure of aircraft wakes has a significant coherent part superimposed with turbulence, about whose structure very little is known. Two simple mechanisms causing refractive index gradients are considered: (A) radial pressure (and therefore density) gradient in a columnar vortex arising from the rotational flow; (B) adiabatic transport of atmospheric fluid within a descending oval surrounding a vortex pair. In the scattering analysis, Tatarski's weak scattering approximation is kept but the usual assumptions of a far field and a uniform incident wave are dropped. For analytical insight, an approximate analysis that invokes, in addition to weak scattering, the far field and wide cylindrical beam assumptions, is also developed and compared with the more general analysis. Reflectivities calculated for the oval (mechanism B) are within 2-13 dBm squared of the measurements (approx. -70 dBm squared) of MIT Lincoln Laboratory at Kwajalein atoll. However, the present predictions have a cut-off away from normal incidence which is not present in the measurements. This implies that the two-dimensional picture is not entirely complete. Estimates suggest that the thin layer of vorticity which is baroclinically generated at the boundary of the oval is turbulent and this may account for

reflectivity away from normal incidence. The reflectivity of a vortex (mechanism A) is comparable to that of the oval (mechanism B) but occurs at a frequency (about 50 MHz) that is lower than those considered in all the experiments to date. This result may be useful because: (i) existing atmospheric radars (known as ST radars) already operate at this frequency and so the present prediction could be verified; (ii) rain clutter is not a problem at this frequency; (iii) mechanism A is more robust because it is independent of atmospheric stratification.

Shariff, K. and Wray, A.

"ANALYSIS OF THE RADAR CROSS-SECTION (RCS) OF AIRCRAFT VORTICES"

American Physical Society, Division of Fluid Dynamics Meeting, November 21-23, 1999, New Orleans, LA

Radar has been proposed as one way to track wake vortices to reduce aircraft spacing. Radar echoes from aircraft wakes are usually interpreted qualitatively using Tatarski's theory of scattering by isotropic atmospheric turbulence. The present work predicts RCS by (1) Keeping the weak scattering approximation but dropping the assumptions of a far-field and a uniform incident wave, neither of which is generally valid for a coherent wake (2) Considering three simple mechanisms for the structure and magnitude of refractive index variations: (i) Radial density gradient in each vortex (ii) Adiabatic transport of atmospheric fluid in the oval surrounding the vortices (iii) 3D fluctuations in the vortex cores. For mechanism (ii) the predictions agree with available data. However, the predictions have a cut-off away from normal incidence which is not present in the measurements due possibly to 3D fluctuations in the oval. The reflectivity of mechanism (i) is comparable but cuts-off at frequencies lower than those considered in the experiment. Finally, we suggest that hot engine exhaust could increase RCS by 40 dB and reveal vortex circulation, provided its mixing is prevented in the laminar vortex.

Shariff, K., Leonard, A., Zabusky, N. J. and Ferziger, J. H.

"ACOUSTICS AND DYNAMICS OF COAXIAL INTERACTING VORTEX RINGS"

Fluid Dynamics Research, Vol. 3, 1988, pp. 337-343.

Using a contour dynamics method for inviscid axisymmetric flow we examine the effects of core deformation on the dynamics and acoustic signatures of coaxial interacting vortex rings. Both 'passage' and 'collision' (head-on) interactions are studied for initially identical vortices. Good correspondence with experiments is obtained. A simple model which retains only the elliptic degree of freedom in the core shape is used to explain some of the calculated features.

Sharman, R.

"NATURE OF AVIATION TURBULENCE"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 1, 2016, Springer International Publishing Switzerland, pp. 3-30.

In-flight encounters with turbulence are a well-known hazard to aviation that is responsible for numerous injuries each year, with occasional fatalities and structural damage. Not only are turbulence encounters a safety issue, they also result in millions of dollars in operational costs to airlines and may cause schedule delays and air traffic management problems. For these reasons, pilots, dispatchers, and air traffic controllers attempt to avoid turbulence wherever possible. Despite these motivations, the accuracy of detection and forecasting turbulence for aviation application is insufficient for acceptable levels of avoidance. This chapter reviews the fundamental problems associated with understanding the properties of aviation-scale turbulence and provides an overview of the advances that are being made in the areas of detection and forecasting. References are included to other chapters in this volume which provide more detail on particular subjects.

Sharman, R. and Lane, T., editors

"AVIATION TURBULENCE"

1st edition, Springer International Publishing Switzerland, 2016.

This book provides a compilation of recent work in aviation turbulence research. The motivation for such a compilation was based on two highly successful internationally attended aviation turbulence workshops in the United States in 2013 and 2014 and four aviation meteorology workshops in Seoul, South Korea. These workshops make it clear that there has not been enough communication between the research community and users who need turbulence information to make operational decisions about where to fly. This book aims to foster that communication, by summarizing recent progress and encouraging future research in this area. The book is structured into five main sections providing background material, reviews, and applications of detection strategies, forecast and nowcast methods and their verification, observational and modeling studies, and finally discussions of future opportunities and research needs. Each major section contains several chapters for a total of 25 chapters. The authors of each chapter were chosen because of their expertise in their area, and every chapter has been peer reviewed by at least two other experts.

Sharman, R. D., Cornman, L. B., Meymaris, G., Pearson, J. and Farrar, T.

"DESCRIPTION AND DERIVED CLIMATOLOGIES OF AUTOMATED IN SITU EDDY-DISSIPATION-RATE REPORTS OF ATMOSPHERIC TURBULENCE"

Journal of Applied Meteorology and Climatology, Vol. 53, 2014, pp. 1416-1432.

The statistical properties of turbulence at upper levels in the atmosphere [upper troposphere and lower stratosphere (UTLS)] are still not well known, partly because of the lack of adequate routine observations. This is despite the obvious benefit that such observations would have for alerting aircraft of potentially hazardous conditions, either in real time or for route planning. To address this deficiency, a research project sponsored by the Federal Aviation Administration has developed a software package

that automatically estimates and reports atmospheric turbulence intensity levels (as EDR defined as epsilon to the 1/3 power, where epsilon is the energy or eddy dissipation rate). The package has been tested and evaluated on commercial aircraft. The amount of turbulence data gathered from these in situ reports is unprecedented. As of January 2014, there are approximately 200 aircraft outfitted with this system, contributing to over 137 million archived records of EDR values through 2013, most of which were taken at cruise levels of commercial aircraft, that is, in the UTLS. In this paper, techniques used for estimating EDR are outlined and comparisons with pilot reports from the same or nearby aircraft are presented. These reports allow calibration of EDR in terms of traditionally reported intensity categories ('light', 'moderate,' or 'severe'). The results of some statistical analyses of EDR values are also presented. These analyses are restricted to the United States for now, but, as this program is expanded to international carriers, such data will begin to become available over other areas of the globe.

Sharman, R., Lane, T. and Schumann, U.

"RESEARCH NEEDS"

In *Aviation Turbulence*, edited by R. Sharman and T. Lane, Chapter 25, 2016, Springer International Publishing Switzerland, pp. 501-518.

The current state of our understanding of aviation-scale turbulence processes and overviews of current detection and forecasting methods were provided in previous chapters of this book. Future progress will require a multipronged multidisciplinary approach from the academic, engineering, and user communities underpinned by advances in our fundamental understanding of turbulence process. The chapter outlines the required research and development, as well as operational needs, required to better understand, observe, and predict turbulence regions.

Sharpe, P. and Agarwal, R. K.

"CONCEPTUAL AND NUMERICAL ANALYSIS OF ACTIVE WINGTIP VORTEX CANCELLATION IN PROPELLER-DRIVEN ELECTRIC AIRCRAFT"

AIAA Paper 2019-1091, January 2019, San Diego, CA.

As battery and electric motor technology continues to advance rapidly, propeller-driven electric aircraft are likely to become a significant part of the aviation market in the near future. One proposed design configuration for electric aircraft involves using large, wingtip-mounted propellers to actively cancel wingtip vortices, a method called active wingtip vortex cancellation (AWVC). By reclaiming part of the kinetic energy that would otherwise be lost to tip vortex formation, drag is decreased. In addition, the induced spanwise flow and upwash from the propeller causes the spanwise lift distribution to remain more uniform at the wingtips, increasing lift.

Shaw, J. and Cole R.

"POTENTIAL BENEFITS OF REDUCING WAKE-RELATED AIRCRAFT SPACING AT THE DALLAS/FORT WORTH INTERNATIONAL AIRPORT"

ATC-304, June 2002, MIT Lincoln Lab., Lexington, MA

Measurements and modeling of wake vortices reveal that the Federal Aviation Administration's (FAA) minimum separation requirements for departing aircraft are often overly conservative. If the separation times following heavy aircraft can be safely reduced, considerable savings will be realized. The Dallas/Fort Worth International Airport (DFW) experiences departure delays daily. Banks of departing aircraft often create a significant queue at the end of the runway, with aircraft waiting between 10-20 minutes to depart. Additional delays occur during weather recovery operations after the terminal airspace has been impacted by thunderstorms. This report produces projected delay and cost benefits of implementing reduced wake spacing for departing aircraft at DFW. The benefits are calculated by simulating aircraft departures during both clear weather and weather recovery operations, using current and possible reduced spacings. The difference in delay values using different separation standards is used to calculate a cost savings to the airlines. The benefits for a single day are extended to a yearly approximation based on the estimated number of days that the separation criteria could be safely reduced.

Shaw, S. T., Hill, J. L. and Villamarin, C. E. M.

"A PRIORI GRID ADAPTATION FOR HELICOPTER ROTOR WAKES USING UNSTRUCTURED AND STRUCTURED-UNSTRUCTURED HYBRID GRIDS"

AIAA Paper No. 2005-0463, Reno, NV, January 2005

A numerical method for the calculation of the flow around isolated helicopter rotors in hovering flight is described. The method is based on the solution of a finite volume formulation of the governing equations on arbitrary cells using a high-resolution Godunov scheme. This capability is exploited to perform calculations on structured-unstructured hybrid grids that have been adapted to the expected location of significant wake structures. The results suggest that if sufficient care is taken in the design of the grid then both the tip vortex and wake sheet can be resolved to significant wake ages. Results are presented that show that the wake of a single bladed rotor could be captured to 3 turns of the tip vortex and two turns of the wake sheet on grids containing less than 3 million cell volumes. It is shown that the use of local adaptation provides improved resolution at a fraction of the cost of calculations based upon structured grid systems. Furthermore, the use of locally structured grids that are aligned with the main flow features provides improved resolution for modest additional computational expense.

Sheard, G. J., Leweke, T. and Hourigan, K.

"THE VORTEX TRAJECTORIES INVOKED BY AN ARRESTING CYLINDER"

Fifth International Conference on CFD in the Process Industries, CSIRO, December 2006, Melbourne, Australia.

The vortex dynamics of a translating circular cylinder which is rapidly arrested is investigated. Simulated particle tracking is employed to identify the trajectory of both the wake vortex pair, and the secondary vortices which are induced as the wake convects over the cylinder. In a similar fashion to the flow past an arresting sphere, each wake vortex induces a counter-rotating vortex, which subsequently self-propel over a range of sometimes surprising trajectories, as the Reynolds number and cylinder translation distance are varied. The results of these simulations have an application in small-scale mixing technologies. At low Reynolds numbers and short translation distances, the wake vortices propel past the cylinder, continuing in the direction of the original cylinder motion. At higher Reynolds numbers, the vortices deviate outwards in circular arcs of increasing curvature, to the point where the vortex pairs collide behind the cylinder. At longer translation distances, Hopf instability destroys the relative symmetry about the wake centerline.

Shebalin, J. V.

"THE THERMAL-VORTEX EQUATIONS"

NASA-CR-178242, Feb. 1987, Old Dominion University, Norfolk, VA.

The Boussinesq approximation is extended to explicitly account for the transfer of fluid energy through viscous action into thermal energy. Ideal and dissipative integral invariants are discussed, in addition to the general equations for thermal-fluid motion.

Sheehan, W. E.

"EVALUATION OF WAKE VORTEX CHARACTERISTICS OF A WIDE-BODY, TRI-JET, COMMERCIAL AIRCRAFT"

Report LR 29620, September 1980, Lockheed California Co, Palmdale, CA.

Under contract to the National Aeronautics and Space Administration, Hugh L. Dryden Flight Research Center, an L-1011 TriStar was used to investigate wake vortex attenuation under various conditions of wing lift distribution, both steady state and oscillatory. This was accomplished by use of various combinations of wing spoiler and aileron operation. The TriStar in all cases was used as the generating aircraft for a probe aircraft as well as low altitude and in-flight photographic evaluation. Wake vortex visualization was obtained through use of smoke generators mounted on the TriStar. Specific wake vortex attenuation data analysis and conclusions are not within the scope of the accomplished contract and are therefore not presented.

Sheftel, D. J.

"OVERVIEW OF POTENTIAL ATC DEVELOPMENTS"

Proceedings 22nd Annual Meeting, Air Traffic Control Assoc., Las Vegas, NV, October 1977, pp. 252-257

The paper presents a broad overview of developments in air traffic control. Projects related to improved aircraft safety are noted including the beacon collision avoidance system, the minimum safe

altitude warning concept, and studies of wind shear. Improvements in controller productivity have been suggested in terms of the electronic tabular display subsystem, the discrete address beacon system, and the automation of flight service stations. Increases in capacity are discussed with reference to the wake vortex avoidance system, the microwave landing system, and airport surface traffic control. Energy conservation is considered and developments in fuel conservation are proposed including flow control. Future air traffic control procedures are identified such as automated en route traffic control, automated terminal service, advanced computer systems, and the incorporation of satellite technology.

Shekarriz, A., Fu, T. C., Katz, J. and Huang, T. T.

"NEAR-FIELD BEHAVIOR OF A TIP VORTEX"

AIAA Journal, Vol. 31, No. 1, January 1993, pp. 112-118

The near-field behavior of a tip vortex trailing behind a low aspect ratio wing, attached to an axisymmetric body, is investigated in this paper. This study was performed in a tow tank and involved the use of particle displacement velocimetry. Evolution of the tip vortex was studied by mapping its instantaneous lateral velocity at several consecutive axial locations. The axial velocity distribution was also measured. Experiments were repeated at various Reynolds numbers and incidence angles. Repeatability was also examined at the same conditions. The results indicate that roll-up is almost complete at the trailing edge and that less than 66% of the root circulation is entrained into the vortex. At chord $Re = 220,000$, the results are steady, and the spatially averaged tangential velocity agrees well with the existing models. At chord $Re < 100,000$ the entire flow structure, including the overall circulation, fluctuates from one experiment to the next. The tangential velocity profiles seem to be dominated by secondary vortices located primarily outside of the vortex core. Axial variations in the flow structure along the parallel middle body, during the same run, are limited to the location of these secondary vortices. The vortex is observed to expand in the afterbody region, without a change in its total strength. For all but one case (chord $Re = 220,000$ and $\alpha = 10$ deg), there is a substantial axial velocity deficit within the vortex core near the trailing edge of the wing. At chord $Re < 100,000$, the axial velocity deficit increases with incidence angle and decreasing chord Re .

Sheldon, D. B.

"VORTEX MOTION PROGRAM"

STC-DOT-TSC-297-71-828, June 1971, Service Technology Corp., Cambridge, MA

The report is the accompanying documentation for a computer program and plotting routine which describes the motion in three dimensions of an aircraft's trailing vortices immediately prior to landing.

Shelekhov, A. P., Shelekhova, E. A., Starchenko, A. V. and Belikov, D. A.

"SIMULATION OF DOPPLER RANDOM ERROR IN WIND PROFILES IN ATMOSPHERIC BOUNDARY LAYER"

1957

15th Coherent Laser Radar Conference Proceedings, June 2009, Toulouse, France, pp. 141-144.

The general equations are proposed for the numerical simulation of Doppler random error in wind profiles in atmospheric boundary layer in the paper. The wind velocity retrievals are calculated by minimizing the least-squares fit cost function, which is the difference between the modeled and observed radial wind velocity. Numerical simulation is based on 'e-l' model of atmospheric turbulence and one-dimensional model of the homogeneous atmospheric boundary layer, which consider diurnal variations of meteorological parameters and the turbulent structure of the atmospheric boundary layer.

Shen, S., Ding, F., Han, J., Lin, Y.-L., Arya, S. P. and Proctor, F. H.

"NUMERICAL MODELING STUDIES OF WAKE VORTICES: REAL CASE SIMULATIONS"

AIAA Paper No. 1999-0755, Reno, NV, January 1999

A three-dimensional large-eddy simulation model, TASS, is used to simulate the behavior of aircraft wake vortices in a real atmosphere. The purpose for this study is to validate the use of TASS for simulating the decay and transport of wake vortices. Three simulations are performed and the results are compared with the observed data from the 1994-1995 Memphis field experiments. The selected cases have an atmospheric environment of weak turbulence and stable stratification. The model simulations are initialized with appropriate meteorological conditions and a post roll-up vortex system. The behavior of wake vortices as they descend within the atmospheric boundary layer and interact with the ground is discussed.

Sheng, C.

"ROLE OF TRANSITION MODELING IN ROTOR HOVER PREDICTIONS"

Journal of Aircraft, Vol. 55, No. 1, January-February 2018, pp. 23-37.

The Langtry-Menter transition model is used to predict the aerodynamic performance of three realistic helicopter and tiltrotor blades in hover: the XV-15 proprotor, the joint-service vertical takeoff/landing experimental rotor, and the S-76 conventional scaled rotor. The role of transition modeling in rotor hover predictions is investigated based on comparative studies using the full turbulence model and the transition model. The subsequent predicted transition phenomena are then validated with the experimental data. The focus of this study is to explore three major issues pertinent to rotor hover predictions: 1) the effect of transition modeling on the rotor aerodynamic prediction, 2) rotor prediction at high thrusts or collective angles, and 3) rotor flow characteristics and their influence on aerodynamic performance. Numerical computations indicate different impacts of the transition modeling on predicting the aerodynamic performance for conventional rotors and proprotors.

Sheng, C. and Zhang, F.

"THE EXPERIMENTAL INVESTIGATION ON THE FORMATION AND DECAY OF VORTEX UNDER INTERACTION OF A JET WITH A CROSSFLOW"

Acta Aerodynamica Sinica, Vol. 6, March 1988, pp. 104-109

Three different vortex systems exist in the flow field for the interaction of a jet with a crossflow: bound vortex, wake vortex, and shear vortex. In this paper, the mechanism of vortex formation is suggested, and interference among vortices is investigated based on observation and measurement by the fluorescent-filament method and seven-hole probes. Finally, the major factors which influence the development and decay of streamwise vortices are also analyzed and discussed.

Shephard, D. J., Kyte, A. P. and Segura, C. A.

"RADAR WAKE VORTEX MEASUREMENTS AT F AND I BAND, "

IEE Colloquium on Radar and Microwave Imaging, London, UK, November 199.

All aircraft generate vortices in their wakes, which are created by the wings as the aircraft produces lift. The wakes consist of two counter-rotating masses of air that are cylindrical in shape and are a potential hazard to a following aircraft. When encountering a vortex, a severe roll that may not be possible to control, can be induced, with the possible catastrophic results. The most hazardous situation is when a small aircraft is following a larger one on landing approach. Aviation regulations specify minimum separations between different types of aircraft when they are receiving an Air Traffic Control service, to ensure that a vortex does not present a hazard to following aircraft. There are two weather conditions that particularly concern ATC authorities. First, those where the vortices persist, and second those which lead to a rapid dispersion of the vortices which could enable the minimum separation between aircraft to be significantly reduced. The successful reduction in separations could improve runway capacity and contribute to the growth in air transport. As of yet there is no reliable all weather method in operation that can determine whether the vortices generated by an aircraft have dispersed, and so, there is an important requirement for a technique or techniques to be developed that can be reliably employed to detect the presence of vortices in the vicinity of airports. This paper describes work undertaken at the GEC-Marconi Research Center to investigate the feasibility of detecting aircraft wake vortices using a microwave radar.

Shepherd, R., Cassell, R., Thapa, R. and Lee, D.

"A REDUCED AIRCRAFT SEPARATION RISK ASSESSMENT MODEL"

AIAA Paper No. 1997-3735, New Orleans, LA, August 1997

A risk assessment methodology has been developed for three scenarios: runway occupancy, wake vortex encounter, and blunder. The operational focus of these scenarios is separation between aircraft on final approach and landing, when flight risks are greater than during any other phase of flight. The result for each scenario is a consolidated risk of incident and accident from all sources applicable to the scenario. In the lateral blunder scenario, there is a well-established target level of safety for the risk of

near misses. For the other scenarios as defined here there is yet no consensus on target measures of safety nor on the target levels of safety for the target measures. The approach used in the model quantifies the connection between several risk measures.

Sheridan, P. F. and Wiesner, W.

"AERODYNAMICS OF HELICOPTER FLIGHT NEAR THE GROUND"

33rd Annual Forum, American Helicopter Society, Washington, DC, May 1977

Nap-of-the-earth (NOE) tactical doctrine will require sustained flight close to the ground at low speeds. All helicopters in the battle zone frequently will be forced to seek cover and fly for long periods of time at very low heights which were formerly encountered only in the takeoff run and during the landing flare or avoided entirely. Such transitory operations within the low-slow flight regime until recently have placed a low priority on aerodynamic research on ground-proximity effects. There is now a compelling need, however, to understand the unsteady and complex flow environment resulting from the interactions of rotor downwash, the ground boundary, and the velocity of translation. Recent studies have begun to provide the required insights for this regime of flight, especially the role of the ground vortex. This anomaly is the dominant feature of the aerodynamic flow field from approximately 10 to 30 knots. The flow associated with the vortex and the loads it produces on the helicopter can be a key factor in many problem areas of flying qualities, component design, performance, and operations.

Sheridan, P. F., Hanker, E. J. and Blake, B. B.

"STUDY OF THE AERODYNAMIC INTERACTIONS OF THE TAIL ROTOR AND FIN"

ARO-15710.2-EG, Boeing Vertol, Philadelphia, PA, June 1983

The results of a wind tunnel investigation of the aerodynamic interaction of the tail rotor and fin are presented. Model loads data were measured for a 1/4.85 scale model of the YUH-61A. Tests were conducted deep in ground effect at wind speeds ranging from 0 to 45 knots; representative of Nap-of-the-Earth. Flow visualization studies provided additional insight into the flow mechanisms at work such as the ground vortex. Distributional flow characteristics, particularly the location and structure of the main rotor tip vortex, were measured by a hot film probe. A variable fin incidence mechanism was incorporated in the model to measure the integrated flow at the empennage. Adverse fin force and tail rotor power variations are measured as functions of airspeed, wind azimuth, tail rotor thrust and main rotor thrust.

Sherratt, S. R.

"RE-CLASSIFICATION OF WAKE VORTEX WAKE GROUPS: A CONTROLLER'S VIEW"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 25-1 - 25-7

There are two main sections to this paper, a consideration of the human factors of implementing an enlarged classification system and a brief look at how enhanced vortex advisory systems and aircraft weight data may be integrated into ATC systems. One of the prime aims of the FAA vortex wake program is the development of revised classifications, followed by the issuing of recommendations for new standards. As an air traffic controller, however, a plea is made for usability. When the groups have been redefined, controllers are the people who must execute the separations with real airplanes. It seems likely that more than the present three ICAO groups will be defined to improve/maintain safety margins and minimize impacts on airport capacity. The past procedure for implementing the classification seems to have been a case of working out the inter and intra group separations first and worrying about how the controller should implement them later. It is suggested that in any future classification scheme the usability of the system could (and should) be tackled first. If controllers find the system difficult to remember or execute, then safety could be compromised, or any theoretical capacity gains negated.

Sherry, J. E.

"RAPID UPDATE CYCLE (RUC) WINDS ALOFT FORECAST ACCURACY AS A FUNCTION OF OUTPUT RESOLUTION"

8th AMS Conference on Aviation, Range, and Aerospace Meteorology, January 1999, Dallas, TX, pp. 391-395.

Resolution based requirements for gridded forecast weather data (i.e., 'highest available resolution') do not necessarily provide the highest available accuracy. Forecast data 50 percent coarser than the model's computational resolution can reduce random noise in the winds aloft forecast to the extent that any loss of information due to decreased resolution is offset and forecast accuracy is therefore not degraded. An 80 km, 50 mb (25 mb above 29,000 feet), and 2-hour RUC II resolution with hourly updates provides on average about a tenth of a knot better winds aloft forecast accuracy than 40 km, 25 mb, and 1 hour. Although analysis data below 29,000 feet can slightly increase winds aloft forecast accuracy when used for forecast interpolation between hours one and three, above 29,000 feet it does not perform any better than forecast hour one and performs slightly worse in jet stream winds.

Sherry, M., Sheridan, J. and Jacono, D. L.

"CHARACTERISATION OF A HORIZONTAL AXIS WIND TURBINE'S TIP AND ROOT VORTICES"

Experiments in Fluids, Vol. 54, 2011, pp. 1417-1 to 1417-19.

The vertical near wake of a model horizontal axis wind turbine has been investigated experimentally in a water channel. The objective of this work is to study vortex interaction and stability of the helical vortex filaments within a horizontal axis wind turbine wake. The experimental model is a geometrically scaled version of the Tjaereborg wind turbine, which existed in western Denmark in the late 1980s. Here, the turbine was tested in both the upwind and downwind configurations. Qualitative flow visualizations using hydrogen bubble, particle streak line and planer laser-induced fluorescence

techniques were combined with quantitative data measurements taken using planar particle image velocimetry. Vortices were identified using velocity gradient tensor invariants. Parameters that describe the helical vortex wake, such as the helicoidal pitch, and vortex circulation, were determined for three tip speed ratios. Particular attention is given here to the root vortex, which has been investigated minimally to date. Signatures of the coherent tip vortices are seen throughout the measurement domain; however, the signature of the root vortex is only evident much closer to the rotor plane, irrespective of the turbine configuration. It is postulated that the root vortex diffuses rapidly because of the turbine support geometries.

Sherwin, L. K., Baggaley, A. W. and Barenghi, C. F.

"ENERGY AND GEOMETRY OF A TANGLE OF VORTEX FILAMENTS"

14th European Turbulence Conference, September 2013, Lyon, France.

By performing a numerical experiment, we show that the energy of a superfluid turbulent vortex tangle is not proportional to its length, as usually assumed in the literature. We discuss the consequence in the interpretation of turbulence decay experiments.

Shevchenko, A. M., Kavun, I. N., Pavlov, A. A. and Zapryagay, V. I.

"REVIEW OF ITAM EXPERIMENTS ON SHOCK WAVE / VORTEX INTERACTION"

Proceedings 21st ICTAM, August 2004, Warsaw, Poland.

The interaction of concentrated streamwise wing-tip vortices and shock waves is investigated at Mach numbers of 3, 4 and 6. Research program included observations of the flowfield in the core of supersonic wing tip vortices, a study of bow shock / vortex interaction and a hypersonic interaction of the streamwise vortex with a Pitot-type inlet.

Shevchenko, A. M., Shmakov, A.S. and Zapryagaev, V. I.

"EXPERIMENTAL STUDY OF AN UNSTEADY FLOWFIELD IN WING WAKE/SHOCK INTERACTIONS"

West-East High Speed Flow Field Conference, November 2007, Moscow, Russia.

A review of a comprehensive experimental study of an unsteady flowfield at different types of interactions of a wing wake with a shock wave is presented. The complex of experimental techniques included a shadowgraph visualization, and pressure fluctuations measurements. Following main topics are discussed: the interaction of a vortex wake with the bow shock generated by the cylinder obstacle; the hypersonic interaction of the vortex wake with a Pitot-type inlet.

Shevchenko, A. M. and Shmakov, A. S.

"EXPERIMENTAL TECHNIQUES AND RESULTS OF INVESTIGATIONS OF AN UNSTEADY FLOWFIELD IN WING WAKES / BOW SHOCK WAVE INTERACTIONS"

International Conference on Methods of Aerophysical Research (ICMAR) 2006, July 2008, Novosibirsk, Russia.

One specific feature of interaction of a vortex wake with a shock wave is the unsteadiness of this process. It is manifested in experimentally observed fluctuations of gas-dynamic parameters of the flow and the changes in the flow structure and interaction region size with time. Recent numerical results showed that the unsteady process may possibly be periodic. A hypersonic interaction of a wing-tip vortex with a Pitot type inlet has been examined at Mach number of 6. It was obtained that the wing-tip vortex is the initiator of self-oscillatory process with salient fundamental. Therefore, two sets of experiments were performed to investigate the unsteady nature of a wing wake / bow shock wave interaction in a wide Mach number range of 3-6. The present paper describes the experimental techniques and results of these studies.

Shevehenko, A. M., Kharitonov, A. and Shmakov, A. S.

"HYPERSONIC VORTEX WAKE BEHIND THE WING AND ITS INTERACTION WITH SHOCK WAVES"

5th European Conference for Aerospace Sciences (EUCASS), July 2013, Munich, Germany

Shock/Vortex interaction is one of the fundamental problems of aerogasdynamics. The absence of numerical and experimental data for hypersonic velocities should be specially noted. Obtaining results for this range of velocities is extremely important for the development of promising flying vehicles (avoiding of catastrophic operation regimes of a hypersonic inlet and improvement of mixing in the combustor). Earlier studies found principal differences in unsteady regimes during the interaction at Mach numbers of 2-4 and at $M = 6$. Therefore, three sets of experiments were performed to study a free vortex wake behind a wing and an unsteady nature of a wing wake / shock wave interaction at Mach number of 6.

Shi, Z., Wu, J. M. and Wu, J. Z.

"SYMMETRIC AND ASYMMETRIC JETS IN A UNIFORM CROSSFLOW"

AIAA Paper No. 1991-0722, Reno, NV, January 1991

This paper presents both physical analysis and numerical study on a jet with different cross-section shape and orientation issuing normally to a uniform crossflow. The production and evolution of the vorticity in this type of flowfield are discussed analytically based on the vorticity and enstrophy transport equation, as well as the boundary vorticity flux formula. It is concluded that although there is no vorticity source within the fluid, a large amount of vorticity generated from solid surfaces will be brought into the fluid by diffusion due to the tangential pressure gradient near the jet-orifice, the wall curvature of the jet-pipe and its edge, and the curl of the wall shear stress vector. It is also described that how the jet wake-vortices are formed from the existing vorticity field by vortex-line bending and

stretching. The unsteady, three-dimensional, incompressible Navier-Stokes equations were solved numerically by using the SOLA algorithm in the present work and the numerical results fully supported the above physical analyses.

Shieh, C. M. and Morris, P. J.

"A NUMERICAL SOLUTION OF ACOUSTIC SCATTERING BY AN AIRCRAFT WAKE VORTEX"

ASA Paper No. 5aEA9, Penn State, University Park, PA, June 1997

Monostatic and bistatic acoustic scattering has been used in studies of the characteristics and motions of the atmosphere. This technique has been successfully implemented in the Monostatic Acoustic Vortex Sensing System (MAVSS) for the measurement of the characteristics of aircraft wake vortices during landing and take-off. In the present study, calculations are performed to simulate the MAVSS. The results of this study are giving information about the acoustic scattering by the vortex, as well as providing a controlled test bed for the instrument's operation. Since the Doppler shifts, characteristic of the vortex velocity, are dependent on the incoherent scattering of the acoustic waves by turbulence advected by the vortex, a statistical model is proposed that describes the turbulence imbedded in the vortex. The simulations are performed using high-order accuracy finite-difference algorithms that have been developed for computational aero-acoustic (CAA) and wave propagation problems.

Shields, M. and Mohseni, K.

"ROLL STALL FOR LOW-ASPECT-RATIO WING"

Journal of Aircraft, Vol. 50, No. 4, July-August 2013, pp. 1060-1069.

The longitudinal aerodynamics of micro aerial vehicles, although not fully understood, have been the subject of several studies in recent years; however, little work has been done to investigate the lateral loading. In this experiment, flat=plate wings with rectangular planforms of aspect ratios $AR = 0.75, 1, 1.5,$ and 3 and tapered planforms of taper ratio $= 0.75, 0.5,$ and 0.25 were placed in the wind tunnel at a Reynolds number of 75000 . Angle-of-attack sweeps were performed at sideslip angles of $0, -5, -10, -15, -20$ and -35 deg, and the side force, yaw moment, and roll moment were measured. Although the side force and yaw moment coefficients were typically negligible, the roll moment coefficient $C_{l_{roll}}$ was found to increase linearly with angle of attack before stalling in a manner reminiscent of a lift curve. This 'roll stall', which has not previously been observed for micro-aerial-vehicle-type wings, is attributed to the upstream tip vortex creating an additional lift component due to its impact on the spanwise variation of effective angle of attack in addition to the force generated by its own low-pressure core. As the downstream tip vortex is convected away from the wing, a net moment is created. Computations of the roll-stability derivative indicate that a micro aerial vehicle in equilibrium flight conditions may experience magnitudes of the roll-stability derivative at the upper limit of, or even above, the range of -0.10 to 0 considered to represent good handling qualities in aircraft.

Shields, W. L.

"AIRCRAFT WAKES: A NEW LOOK AT A CLASSICAL PROBLEM"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 1-8

The paper presents a frame of reference for the Wake Turbulence Symposium, first by elucidating some historical aspects of the aircraft wake problem, then by recounting the genesis of the AFOSR wake turbulence research program and finally by commenting on some of the challenging research opportunities contained within the wake problem.

Shirgaonkar, A. A. and Lele, S. K.

"SIMULATIONS OF AIRCRAFT WAKE-EXHAUST MIXING USING LES: CONTRAIL FORMATION IN THE NEAR FIELD"

AIAA Paper No. 2005-4909, Toronto, Canada, June 2005

Aircraft flying at cruise conditions produce contrails if conditions are favorable. Persistent contrails and contrail-induced cirrus clouds are thought to contribute to climate change on global scales. The dynamics of jet exhaust plays an important role in determining properties and persistence of contrails. The present study focuses on three-dimensional Large Eddy Simulations (LES) of aircraft wake and exhaust jets at cruise conditions in the extended near-field (1-2 minutes or 15-35 km behind the airplane). An attempt is made to reproduce realistic conditions by including jet turbulence, stratification, and jet buoyancy. We describe a mixed Eulerian-Lagrangian approach to computational modeling of contrail evolution. We present results from small domain calculations for the water vapor content and ice growth in the aircraft wake. Effects of stratification and atmospheric temperature are studied.

Shirgaonkar, A. A. and Lele, S. K.

"LARGE EDDY SIMULATION OF EARLY STAGE CONTRAILS: EFFECT OF ATMOSPHERIC PROPERTIES"

AIAA Paper No. 2006-1414, Reno, NV, January 2006

Prediction of growth and persistence of aircraft condensation trails involves uncertainties arising from numerous factors. It is sensitive to the atmospheric thermodynamic variables. Ambient relative humidity (RH) and temperature are themselves difficult to predict accurately, and they also affect the contrail growth. This study carries out Large Eddy Simulations (LES) of aircraft wake-contrail system to find the sensitivity of contrails to atmospheric conditions. A mixed Eulerian-Lagrangian approach is used to simulate the wake-jet flow and ice particle evolution. The microphysics model used is described. Unsaturated, saturated, and supersaturated atmospheric conditions are studied. Quantitative comparison for total ice amount and particle statistics is presented for various values of ambient temperature, RH, and jet exhaust temperature. The focus is on early stage (up to 15 sec) ice particle growth of a typical subsonic transport aircraft.

Shirgaonkar, A. A. and Lele, S. K.

"INTERACTION OF VORTEX WAKES AND BOUYANT JETS: A STUDY OF TWO-DIMENSIONAL DYNAMICS"

Physics of Fluids, Vol. 19, 2007, pp. 086601-1 - 086601-11.

The dynamics of aircraft wakes are affected by buoyancy forces resulting from stratification and exhaust jets. In this study the influence of jet buoyancy on the descent and spacing of a trailing vortex pair is characterized using a two-dimensional model problem. Results from laminar wake-jet simulations with and without stratification are presented. In addition to the vorticity dynamics of wakes in a stratified medium reported in the existing literature, the presence of the jets causes additional mechanisms which affect the wake behavior. The two opposite-signed components of baroclinic vorticity induced by the jets result in strengthening of the primary trailing vortices and produce an induced velocity on the primary vortices. Both components cause an overall reduction in the primary vortex spacing and a faster vortex wake descent. The entrainment of jet fluid into the vortex cores and detrainment into the atmosphere is illustrated. The influence of buoyancy on jet exhaust fluid transport and total circulation is investigated.

Shirgaonkar, A. A. and Lele, S. K.

"LARGE EDDY SIMULATION OF EARLY STAGE AIRCRAFT CONTRAILS"

Report TF-100, April 2007, Stanford University, Dept. of Mechanical Engineering, Stanford, CA.

Aircraft contrails at cruise present a unique problem in atmospheric sciences due to their location where other anthropogenic sources of particulate emissions are absent, and due to their potential impact on the Earth's radiative balance. We investigate the behavior of two-dimensional aircraft wakes containing exhaust jets. A mechanism is identified by which the jet-induced baroclinic vorticity influences the wake dynamics. The jets strengthen the primary vorticity and reduce the primary vortex pair spacing, causing accelerated wake descent. Three-dimensional LES of contrails are carried out for the first 20 second duration of contrail life, starting at 1 second behind the aircraft. The initial conditions at 1 s correspond to a typical large subsonic aircraft. Three different regimes of early contrail growth are found, which are controlled by jet humidity, jet turbulence and ice particle-induced perturbations, and ambient relative humidity with respect to ice, respectively.

Shivamoggi, B. K. and Uberoi, M. S.

"CONTRIBUTIONS TO THEORY OF VORTEX BREAKDOWN"

Acta Mechanica, Vol. 41, 1981, pp. 211-215.

A study is made of vortex breakdown in stratified flows. It is found that a positive stratification in the vortex, i.e., the density increasing away from the axis, has the effect of postponing the vortex

breakdown and vice versa. Next, further considerations are made of Benjamin's theory of vortex breakdown.

Shivananda, T. P, McMahon, H. M. and Gray, R. B.

"SURFACE PRESSURE MEASUREMENTS AT THE TIP OF A MODEL HELICOPTER ROTOR IN HOVER"

Journal of Aircraft, Vol. 15, No. 8, August 1978, pp. 460-467.

Detailed blade-tip surface pressure distribution data for a single-bladed model helicopter rotor in hover are presented. The pressure measurements were made along the chordwise direction at six spanwise stations outboard of the 94 percent radial location on the rotor blade. Data were taken at blade collective pitch angles of 0, 6.2 and 11.4 degrees at Reynolds numbers (based upon rotor tip speed and chord) of 544000 and 736000. The points of inception of the primary vortex inferred from the pressure data agree with those noted by other investigators using surface flow visualization techniques. The presence of both a primary and a secondary vortex near the rotor tip at a pitch angle of 11.4 degrees is observed. Normal and chordwise force coefficients obtained by integrating the pressure data are also presented.

Shizawa, T. and Endo, S.

"PRODUCTION AND DIFFUSION MECHANISM OF LONGITUDINAL VORTICES DOWNSTREAM OF ACTIVE VORTEX-GENERATORS PAIR"

AIAA Paper No. 2007-1422, Reno, NV, January 2007

This paper focuses on the time-dependent convection, production, and diffusion mechanism of longitudinal vortices downstream of a pair of active vortex generators controlling angle of pitch with common flow up configuration. Controlling turbulent shear flow skillfully is one of the most challenging topics. The most effective control device is to employ longitudinal vortices for the boundary layer manipulation and local heat transfer modification. Therefore, it is important to understand the transient interacting processes between turbulent boundary layer and longitudinal vortices. The interests of this paper are to make clear the time dependent characteristics of the interacting region and to make clear the dominant time scales. Time-dependent mechanism of longitudinal vortices is clarified by evaluating each term in streamwise vorticity transport equation by the use of newly developed rotating X-array hot-wire anemometer which can measure full components of turbulent Reynolds stresses.

Shkarayev, S., Su, E. and Zhao, L.

"AERODYNAMICS OF WING WITH OSCILLATING WINGTIP FLAPPER"

AIAA Paper 2016-3119, June 2016, Washington, DC.

1967

In the present study, a membrane oscillating flapper was pivotally attached to the wingtip of a conventional rigid wing. Stroke-average aerodynamic forces were measured for the range of the flapping frequency, showing significant increase in the lift coefficient and lift-to-drag ratio for the wing with a flapper. Wake structures were visualized using smoke-wire techniques and 2D phase-locked PIV. Major vortex patterns were deduced from the observations: primary and secondary undulating vortices and a vortex ring. The primary vortex oscillates in both vertical and horizontal planes. At the beginning of the downstroke, the secondary vortex sheds from the flapper then merges with the primary one at the beginning of the upstroke. The vortex ring sheds from the flapper during the second half of the upstroke and on pronation. The circulation of undulating vortices and of the ring decreases significantly with increasing distance from the wing downstream, while the decrease of the vortex core size is minimal.

Shmakov, A. S. and Shevchenko, A. M.

"AN EXPERIMENTAL STUDY OF THE VORTEX WAKE AT MACH NUMBER OF 3"

Proceedings of the XXV Conference on High-Energy Processes in Condensed Matter (HEPPCM 2017), AIP Conference Proceedings, Vol. 1893, 2017, pp. 030089-1 to 030089-5.

The results of experimental study of the flow in the wing wake at Mach number of 3 are presented. These experiments extend the data obtained in the same experimental setup at Mach numbers 2.5 and 4. Experiments were carried out in supersonic wind tunnel T-325 of ITAM SB RAS. Rectangular half-wing with sharp edges with a chord length of 30 mm and semispan of 95 mm was used to generate vortex wake. Experimental data were obtained in two cross sections located 1.5 and 6 chord length downstream of the trailing edge at wing angle of attack of 10 degrees. Constant temperature hot-wire anemometer was used to measure disturbances in supersonic flow. Hot-wire anemometer was made of a tungsten wire with a diameter of 10 microns and length of 1.5 mm. Schlieren flow visualization were performed. As a result, the position and size of the vortex core in the wake of a rectangular wing were determined. For the first time mass flow distribution and its pulsations in the supersonic longitudinal vortex was measured at Mach number of 3.

Shmakov, A. S., Shevchenko, A. M. and Kharitonov, A. M.

"VISUALIZATION AND SIMULTANEOUS PULSATION CHARACTERISTIC MEASUREMENT IN PROBLEMS OF VORTEX WAKE/SHOCK INTERACTION"

VIIth International Conference on the Methods of Aerophysical Research (ICMAR 2014), July 2014, Novosibirsk, Russia.

The paper presents methods and examples of data processing visualization and pressure fluctuations in the experimental study of the fast unsteady interaction of vortex wake behind the wing with the bow shock wave in front of a cylinder with a flat end.

Shmakov, A. S., Shevchenko, A. M., Yatskikh, A. A. and Yermolaev, Yu. G.

"MASS FLOW AND ITS PULSATION MEASUREMENTS IN SUPERSONIC WING WAKE"

International Conference on the Methods of Aerophysical Research (ICMAR 2016), AIP Conference Proceedings, Vol. 1770, 2016, pp. 030019-1 to 030019-6.

The results of experimental study of the flow in the wing wake are presented. Experiments were carried out in supersonic wind tunnel T-325 of ITAM SB RAS. Rectangle half-wing with sharp edges with a chord length of 30 mm and semispan 95 mm was used to generate vortex wake. Experimental data were obtained in the cross section located 6 chord length downstream of the trailing edge at Mach numbers of 2.5 and 4 and at wing angles of attack of 4 and 10 degrees. Constant temperature hot-wire anemometer was used to measure disturbances in supersonic flow. Hot-wire was made of a tungsten wire with a diameter of 10 microns and length of 1.5 mm. Schlieren flow visualization was performed. As a result, the position and size of the vortex core in the wake of a rectangular wing were determined. For the first time experimental data on the mass flow distribution and its pulsations in the supersonic longitudinal vortex were obtained.

Shmilovich, A., Yadlin, Y., Clark, R. and Leopold, D.

"APPARATUS AND METHOD FOR THE CONTROL OF TRAILING WAKE FLOWS"

US Patent 7,100,875 B2, September 2006.

A system and method for dissipating vortices that form at the wingtips on aircraft and from other airfoils. A jet air stream is discharged in a location at or proximate to the outer end portion of the airfoil into the vortex flow, and the jet air stream is moved cyclically back and forth. The cyclic movement can be at lower or higher frequencies to alleviate at least in part intensity of the vortex or accelerate instability of the vortex which leads to vortex dissipation.

Shmilovich, A., Yadlin, Y., Clark, R. and Leopold, D.

"APPARATUS AND METHOD FOR THE CONTROL OF TRAILING WAKE FLOWS"

US Patent 7,597,289 B2, October 2009.

A system and method for dissipating vortices that form at the wingtips on aircraft and from other airfoils. A jet air stream is discharged in a location at or proximate to the outer end portion of the airfoil into the vortex flow, and the jet air stream is moved cyclically back and forth. The cyclic movement can be at lower or higher frequencies to alleviate at least in part intensity of the vortex or accelerate instability of the vortex which leads to vortex dissipation.

Shmilovich, A., Yadlin, Y., Clark, R. and Leopold, D.

"SYSTEMS AND METHODS FOR DESTABILIZING AN AIRFOIL VORTEX"

US Patent 7,661,629 B2, February 2010.

Apparatuses and methods for the controlled trailing wake flows. An apparatus in accordance with one embodiment is directed to an aircraft system that includes an airfoil having first and second oppositely facing flow surfaces and a tip. The system can further include a vortex dissipation device including a fluid flow nozzle, a valve device, and a controller. The fluid flow nozzle can be coupled to a source of pressurized fluid and can include an orifice positioned to direct a flow of fluid outwardly from the tip. The valve device can be coupled in fluid communication with the fluid flow nozzle to selectively control the flow passing through the orifice. The controller can be coupled to the valve device to direct the operation of the valve device. Accordingly, the vortex dissipation device can be activated to accelerate the rate at which vortices (e.g., wing tip vortices) dissipate after they are generated.

Short, B. J. and Jacobsen, R. A.

"EVALUATION OF A WAKE VORTEX UPSET MODEL BASED ON SIMULTANEOUS MEASUREMENTS OF WAKE VELOCITIES AND PROBE-AIRCRAFT ACCELERATIONS"

NASA-TM-78561, March 1979, NASA Ames Research Center, Moffett Field, CA

Simultaneous measurements were made of the upset responses experienced and the wake velocities encountered by an instrumented Learjet probe aircraft behind a Boeing 747 vortex-generating aircraft. The vortex-induced angular accelerations experienced could be predicted within 30% by a mathematical upset response model when the characteristics of the wake were well represented by the vortex model. The vortex model used in the present study adequately represented the wake flow field when the vortices dissipated symmetrically and only one vortex pair existed in the wake.

Shortle, J. and Allocco, M.

"APPLYING QUALITATIVE HAZARD ANALYSIS TO SUPPORT QUANTITATIVE SAFETY ANALYSIS FOR PROPOSED REDUCED WAKE SEPARATION CONOPS"

6th USA/Europe ATM R&D Seminar, April 2005, Paper 82, Baltimore, MD

This paper describes a scenario-driven hazard analysis process to identify, eliminate, and control safety-related risks. Within this process, we develop selective criteria to determine the applicability of applying engineering modeling to hypothesized hazard scenarios. This provides a basis for evaluating and prioritizing the scenarios as candidates for further quantitative analysis. We have applied this methodology to proposed concepts of operations for reduced wake separation for closely spaced parallel runways. For arrivals, the process identified 43 core hazard scenarios. Of these, we classified 12 as appropriate for further quantitative modeling, 24 that should be mitigated through controls, recommendations, and / or procedures (that is, scenarios not appropriate for quantitative modeling), and 7 that have the lowest priority for further analysis.

Shortle, J. F.

"A COMPARISON OF WAKE-VORTEX MODELS FOR USE IN PROBABILISTIC AVIATION SAFETY ANALYSIS"

Proceedings of the 25th International System Safety Conf., System Safety Society, 2007, Baltimore, MD, pp. 581-589.

The goal of this paper is to address part of a larger safety issue in aviation. What is the probability that a landing aircraft flies through a wake vortex generated by the aircraft in front of it and subsequently crashes? An important element needed to address this overall research question is a model to predict the evolution of wake vortices in time. Several such models have been developed and published in the literature. However, accurate prediction of wakes is inherently difficult. The objective of this paper is to assess the performance of different wake models when imbedded within a larger probabilistic safety analysis. This paper does not attempt to assess the accuracy of wake models by comparison to actual data. The purpose here is to compare the models with each other, and evaluate differences in performance when used within a safety assessment.

Shortle, J. F. and Jeddi, B. G.

"PROBABILISTIC ANALYSIS OF WAKE VORTEX HAZARDS FOR LANDING AIRCRAFT USING MULTILATERATION DATA"

TRB Annual Meeting, Washington, DC, 2007

Wake vortices are a safety hazard to landing aircraft. A landing aircraft that encounters a wake may roll, resulting in a fatal crash if the roll is severe enough and/or if the aircraft is low enough to the ground. Therefore, aircraft are separated by a sufficient distance to ensure that wakes have time to decay in strength. However, because of the inherent variability in wake behavior and aircraft separation and position, there is still a possibility for a wake encounter. The objective of this paper is to estimate the probability of such encounters. This paper presents a hybrid simulation methodology. The approach is hybrid in the sense that part of the simulation is conducted using a direct data feed of flight-track data, while the other part is obtained by simulation of wake-evolution models. We demonstrate the approach on a one-week sample of flight tracks to predict the frequency of potential wake alerts. In this paper a wake alert is defined to be an event where the trailing aircraft is in a region of space where the wake is likely to be. We show how the results depend on atmospheric conditions and other model parameters.

Shortle, J. F., Zhang, Y. and Wang, J.

"STATISTICAL CHARACTERISTICS OF AIRCRAFT ARRIVAL TRACKS"

Journal of the Transportation Research Board, No. 2177, 2010, pp. 98-104.

The statistical characteristics of flight tracks is a critical component of safety analysis models. This paper presents an analysis of multilateration data that uses an extension of an algorithm. Key results are as follows: the separation distribution does not appear to change much at different points along the approach path. The left tail of separation (corresponding to the smallest separation values) decays

faster than a normal distribution. This is positive from a safety perspective. If this behavior is extrapolated beyond the observed data, one can conjecture that smaller separations have probabilities that rapidly decay to effectively zero. Lateral positions near the threshold do not appear to be heavy tailed, either. Finally, estimates of the final approach separation variability are consistent with previously published results.

Shrager, J. J.

"A SUMMARY OF HELICOPTER VORTICITY AND WAKE TURBULENCE PUBLICATIONS WITH AN ANNOTATED BIBLIOGRAPHY"

FAA-RD-74-48, May 1974, Federal Aviation Administration, Atlantic City, NJ

A review of all literature published since 1964 relating to helicopter vortex systems and wake turbulence was made. The results of this review are evaluated and summarized and conclusions are drawn relative to that review. The documents are grouped in general categories, and this is further supplemented by an annotated bibliography and author's index. Also incorporated in the review is a comparative analysis of rotary-wing versus fixed-wing circulation intensity time history.

Shrestha, B. and Joseph, E.

"RETRIEVAL OF PM SUB 2.5 PROFILE USING THE DOPPLER LIDAR ACROSS NEW YORK STATE MESONET"

19th Coherent Laser Radar Conference (CLRC), Paper P22, June 2018, Okinawa, Japan.

The University of Albany has developed a Mesonet, a network of 17 enhanced sites across the NY state, comprised of Doppler Lidar, Microwave Radiometer and Sun Photometer. The goal of the network is to enhance information content by combining all sensors for Numerical Weather Prediction and air quality forecasting. The vertical profile of PM sub 2.5 is very important for the study of air quality and its forecasting. The commonly used method only estimates surface PM sub-2.5, which is based on its relationship with Aerosol Optical Depth (AOD) from satellite and Sun Photometer. In this study, the relationship of aerosol extinction coefficient retrieved from the Doppler Lidar inversion, with surface PM sub 2.5 is presented. Then, the PM sub 2.5 profile is retrieved using the extinction coefficient profile. Three cases of high, low and medium PM sub 2.5 are presented and compared with surface PM sub 2.5 measurements. The experiment results show that Doppler Lidar can be used to continuously monitor PM sub 2.5 profile and hence, the retrieval technique when applied throughout the network is a good sign for real time 3D monitoring of PM sub-2.5.

Shtern, V. and Hussain, F.

"VORTEX BREAKDOWN AS A CATASTROPHE"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany, pp. 297-306.

By studying swirling viscous jets, we develop a new explanation of vortex breakdown, show how solution non-uniqueness appears through cusp and fold catastrophes as the Reynolds number Re increases, and obtain analytical solutions for Re approaching infinity. Although inviscid theories also involve fold catastrophe, they have a strong limitation: the dependence of the head H and circulation G on stream function S is undetermined inside a recirculatory zone. Analytical continuation and stagnation zone models used to resolve this indeterminacy appear inadequate for swirling jets: $H(S)$ and $G(S)$, which we obtain here by the inviscid limit, differ from those based on the inviscid theories. We therefore suggest a new model consistent with the limiting transition. Also, we analyze turbulent vortex breakdown with a conical wake which has been recently observed at large Re .

Shtern, V. and Hussain, F.

"COLLAPSE, SYMMETRY BREAKING, AND HYSTERESIS IN SWIRLING FLOWS"

Annual Review of Fluid Mechanics, Vol. 31, 1999, pp. 537-56.

The paper reviews striking features of swirling flows, collapse, swirl generation, vortex breakdown, hysteresis, and axisymmetry breaking, and the mechanisms involved with the help of conical similarity solutions of the Navier-Stokes equations. The strong accumulation of axial and angular momenta, observed in tornadoes and flows over delta wings, corresponds to collapse, i.e., the singularity development in these solutions. Bifurcation of swirl explains the threshold character of swirl development in capillary and electro vortex flows. Analytical solutions for fold catastrophes and hysteresis reveal why there are so few stable states and why the jump transitions between the states occur, features typical of tornadoes, of flows over delta wings, and in vortex devices. Finally, the divergent instability explains such effects as the splitting of a tornado and the development of spiral branches in tree and near-wall swirling flows.

Shtern, V., Borissov, A. and Hussain, F.

"VORTEX SINKS WITH AXIAL FLOW: SOLUTION AND APPLICATIONS"

Physics of Fluids, Vol. 9, No. 10, October 1997, pp. 2941-2959.

In this paper we develop a new class of analytical solutions of the Navier-Stokes equations and suggest ways to predict and control complex swirling flows. We consider vortex sinks on curved axisymmetric surfaces with an axial flow and obtain a five-parameter solution family that describes a large variety of flow patterns and models fluid motion in a cylindrical can, whirlpools, tornadoes, and cosmic swirling jets. The singularity of these solutions on the flow axis is removed by matching them with swirling jets. The resulting composite solutions describe flows, consisting of up to seven separation regions (recirculatory 'bubbles' and vortex rings), and model flows in the Ranque-Hilsch tube, in the meniscus of electrosprays, in vortex breakdown, and in an industrial vortex burner. The analytical solutions allow a clear understanding of how different control parameters affect the flow and guide selection of optimal parameter values for desired flow features. The approach permits extension to swirling flows with heat transfer and chemical reaction, and have the potential of being significantly

useful for further detailed investigation by direct or large-eddy numerical simulations as well as laboratory experimentation.

Shugaev, F. V., Cherkasov, D. Y. and Solenaya, O. A.

"ACOUSTIC RADIATION BY 3D VORTEX RINGS IN AIR"

Aerospace, Vol. 2, November 2015, pp. 627-636.

Acoustic radiation emitted by three-dimensional (3D) vortex rings in air has been investigated based on the unsteady Navier-Stokes equations. Power series expansions of the unknown functions with respect to the initial vorticity which is supposed to be small are used. In such a manner the system of the Navier-Stokes equations is reduced to a parabolic system with constant coefficients at high derivatives. The initial value problem is as follows. The vorticity is defined inside a toroid at $t = 0$. Other gas parameters are assumed to be constant throughout the whole space at $t = 0$. The solution is expressed by multiple integrals which are evaluated with the aid of the Korobov grids. Density oscillations are analyzed. The results show that the frequency band depends on the initial size of the vortex ring and its helicity. The presented data may be applied to the study of a flow in a wake region behind an aerodynamic body.

Shur, M., Strelats, M., Travin, A. and Spalart, P. R.

"TWO NUMERICAL STUDIES OF TRAILING VORTICES"

AIAA Paper No. 1998-0595, Reno, NV, January 1998

Two types of trailing-vortex flows are calculated based on the Reynolds Averaged Navier-Stokes equations coupled with three turbulence models: the one-equation Spalart-Allmaras model, the SA model with a rotation/curvature correction, and the two-equation k- ω model of Menter. The first flow type contains one or more vortex pairs in ground effect with side wind. The second type is the trailing-vortex system behind a generic civil aircraft model at high lift, for which we have experimental data of de Bruin et al. The major conclusion of the study performed is that the rotation/curvature correction proposed for the SA model actually provides much better predictions of both flows, by drastically reducing the diffusion of the vorticity.

Shustov, A. V.

"MODELING OF AEROSOL PARTICLES DISTRIBUTION IN AIRCRAFT WAKE"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 324-328

The work adduces results obtained from development of space-time relationships for distribution of the aircraft wake aerosols. The relationships are further employed to model signals supplied to the mobile laser system. The model is based on a partial differential equation, which is being solved by the

1974

characteristic method. A numerical test calculation of aerosol particles concentration time-dependence, where the particle size is specified, serves to illustrate effectiveness of the proposed model (the MATLAB program has been employed for the calculations).

Silverman, P.

"VORTEX CASES - AT A TURBULENT CROSSROADS"

J. Air Law and Commerce, Vol. 39, Summer 1973, pp. 325-342

Discussion of some of the legal aspects of the problem of wake turbulence, a phenomenon to which a substantial number of air crashes has been attributed in recent years. The duty of air traffic controllers to warn of possible wake turbulence and the nature of this warning are examined. Several court cases are reviewed to show how the courts look at wake turbulence, and some controversial cases are analyzed. During 1968-1970, more than \$3,000,000 have been paid by the United States Government in indemnities where air traffic controllers were judged to have been negligent in helping prevent air crashes that had been caused by wake turbulence. It is felt that wake turbulence accidents cannot be expected to cease to happen, but the trend against the Government may ease sufficiently to permit a greater sharing of responsibility by pilots, the flying schools, and air taxi operators that employ them.

Silverstein, A. and Katzoff, S.

"DESIGN CHARTS FOR PREDICTING DOWNWASH ANGLES AND WAKE CHARACTERISTICS BEHIND PLAIN AND FLAPPED WINGS"

NACA TR-648, January 1939, NACA Langley Memorial Aeronautical Lab., Langley Field, VA

Equations and design charts are given for predicting the downwash angles and the wake characteristics for power-off conditions behind plain and flapped wings of the types used in modern design practice. The downwash charts cover the cases of elliptical wings and wings of taper ratios 1, 2, 3, and 5, with aspect ratios of 6, 9, and 12, having flaps covering 0, 40, 70, and 100 percent of the span. Curves of the span load distributions for all these cases are included. The wake width and the distribution of dynamic pressure across the wake are given in terms of the profile-drag coefficient and the distance behind the wing. A method of estimating the wake position is also given.

Silverstein, A., Katzoff, S. and Bullivant, W. K.

"DOWNWASH AND WAKE BEHIND PLAIN AND FLAPPED AIRFOILS"

NACA TR-651, January 1939, NACA Langley Aero. Lab., Langley Field, VA

Extensive experimental measurements have been made of the downwash angles and the wake characteristics behind airfoils with and without flaps and the data have been analyzed and correlated with the theory. A detailed study was made of the errors involved in applying lifting-line theory, such as the effects of a finite wing chord, the rolling-up of the trailing vortex sheet, and the wake. The

1975

downwash angles, as computed from the theoretical span load distribution by means of the Biot-Savart equation, were found to be in satisfactory agreement with the experimental results. The rolling-up of the trailing vortex sheet may be neglected, but the vertical displacement of the vortex sheet requires consideration. Using a theoretical treatment indicated by Prandtl, it has been possible to generalize the available experimental results so the predictions can be made of the important wake parameters in terms of the distance behind the airfoil trailing edge and the profile-drag coefficient. The method of application of the theory to design and the satisfactory agreement between predicted and experimental results when applied to an airplane are demonstrated.

Simand, C., Chilla, F. and Pinton, J.-F.

"INHOMOGENEOUS TURBULENCE IN THE VICINITY OF A LARGE-SCALE COHERENT VORTEX"

Europhysics Letters, Vol. 49, No. 3, 2000, pp. 336-342.

We study the statistics of turbulent velocity fluctuations in the neighborhood of a strong large-scale vortex at large Reynolds number. At integral scale, the vortex dynamics can be either stable or unstable. We observe that at each distance from the vortex core, the velocity spectrum has a power law 'inertial range' of scales and that intermittency is also present. The texture of turbulence is also influenced by the large-scale dynamics of the vortex: as measurements are made closer to the core the spectrum scaling exponents, the energy transfer rate (estimated via the third-order structure function) and the intermittency characteristics follow different evolutions in each regime.

Simand, C., Chilla, F. and Pinton, J.-F.

"STRUCTURE, DYNAMICS AND TURBULENCE FEATURES OF A CONFINED VORTEX"

Lecture Notes in Physics, Vol. 555, 2000, pp. 291-29.

We study inhomogeneous turbulence in the presence of a strong large-scale vortex. To understand its influence on the observed properties of the turbulence, we determine the large-scale structure and dynamics of the flow, using LDV and visualizations of the motion of solid particles. We then describe the small scales fluctuations of velocity. We show that the features of turbulence vary with the distance to the vortex, and are also influenced by its dynamics.

Simons, I. A., Chan, W. Y. F., Perry, F. J., Brown, R. E. and Ahlin, G. A.

"MODELLING THE MEAN FLOW THROUGH A ROTOR IN AXIAL FLIGHT INCLUDING VORTEX RING CONDITIONS"

The 2nd International Basic Research Conference on Rotorcraft Technology, Nanjing, China, November 2005.

An engineering model for the mean flow through a rotor in descending flight, based on a vortex tube element representation of the wake, proposed by Wang is re-examined and related to other theoretical

approaches. The assumptions, on which the model is based and the properties of its vortex tube formulation are described and examined in the light of recent detailed theoretical calculations. This information is used to expose important underlying physical issues.

Simons, I. A., Pacifico, R. E. and Jones, J. P.

"THE MOVEMENT, STRUCTURE, AND BREAKDOWN OF TRAILING VORTICES FROM A ROTOR BLADE"

ARC-28993, April 1967, Aeronautical Research Council, London, England.

The results of some flow visualization experiments on the trailing vortices from a model rotor blade are presented. It is found that, at low tip-speed ratios, trailing vortices close to the leading edge of the disc first pass up through the disc before entering the main flow field. At the rear of the disc, the vortices maintain a regular pattern relative to each other. The vortices are fully rolled-up in about 60 degrees of azimuth movement of the blade. Measurements with a hot-wire anemometer show that the vortex core is about one-tenth of a blade chord in diameter, which is consistent with a laminar core state. Outside the core, the velocity field is irrotational.

Simpson, R. G, Ahmed, N. A. and Archer, R. D.

"NEAR FIELD STUDY OF VORTEX ATTENUATION USING WING-TIP BLOWING"

Aeronautical Journal, March 2002, pp. 117-120

Tip blowing was investigated in a wind tunnel as an active flow control scheme to attenuate the trailing vortex generated by a rectangular wing. Tip blowing was introduced at the quarter chord, at a constant blowing coefficient of 0.065, and in the forms of both straight Coanda jets. Hot-wire measurements were made at one semi-wing span downstream for both flapped and non-flapped wing configurations. The straight and Coanda jets provided similar results. Relative to the no-blowing baseline case, a reduction in the peak tangential velocity up to 55 percent was achieved. The associated enlargement of the core was by a factor as large as 2.5, with an attenuation of streamwise vorticity around 20 percent. With blowing, the axial velocity in the vortex core also transits from a jet-like to a wake-like profile, suggesting a modification of the spanwise loading on the wing. Blowing was also seen to have caused the vortex core migrate upward and outboard, which suggested a decrease in the induced drag. It is recommended that future studies should include an overall aerodynamic performance of the wing with and without blowing.

Simpson, R. J. S., Palacios, R. and Murua, J.

"INDUCED-DRAG CALCULATIONS IN THE UNSTEADY VORTEX LATTICE METHOD"

AIAA Journal, Vol. 51, No. 7, July 2013, pp. 1775-1779.

Unsteady aerodynamics methods that use lifting-surface approximations require the solution of the leading-edge suction in their induced-drag calculations. Results of two force-calculation methods used

in the unsteady vortex lattice method (the Joukowski method and the Katz and Plotkin method) have been presented with a focus on the calculation of unsteady induced drag. Comparisons of both methods have been made with analytical solutions for the induced drag of plunging and pitching flat-plate airfoils. It was shown that the methods converge equally well to the analytical solutions as finer discretizations are used.

Simpson, T. R.

"PRELIMINARY ANALYSIS OF CIVIL AVIATION ACCIDENTS, JANUARY 1964 -DECEMBER 1972"

FAA-AVP-75-2, April 1975, Mitre Corp., McLean, V.

This document presents a preliminary analysis of all civil aviation accidents which occurred within the United States and its territories and possessions during the nine-year period from January 1964 to December 1972. An overview is first presented which identifies the distribution of these accidents by user class, by aircraft type, and by phase of flight. Due to earlier detailed studies of midair collisions and the small number of fatalities that occurred in accidents when the aircraft were on the ground, the category of single aircraft airborne accidents was selected for further examination. Accidents that occurred during landing and accidents involving encounters with wake vortices were given special emphasis.

Sinclair, P. C.

"THE LOWER STRUCTURE OF DUST DEVILS"

Journal of the Atmospheric Sciences, Vol. 30, November 1973, pp. 1599-1619.

Measurements from an extensive field program in the desert near Tucson, Ariz., are used to formulate a quantitative dust devil model. The model is based on measurements of temperature, pressure and wind velocity taken from a mobile instrumental tower near and within dust devils at levels of 6, 17 and 30 ft. Three dust devil penetrations are analyzed with respect to the temperature, pressure and wind velocity profiles contained in a plane defined by the dust devil axis (or local vertical) and the direction of motion. These profiles corroborate earlier preliminary measurements by Sinclair and thus firmly establish the existence of the warm, low-pressure core of the dust devil. Maximum temperature and pressure variations within the dust devil varied from 4 to 8 C and 2.5 to 4.5 mb. The most significant result of the measurement program was the discovery of a down current or a region of markedly reduced vertical motion along and surrounding the sloping dust devil axis. Immediately outside the down current, the vertical velocity reaches positive peak values and then diminishes rapidly with respect to increasing radius. Superimposed on this motion is a strong rotary and radial motion which results in a combined flow pattern similar to that of a helical vortex. The measurements are synthesized into a dust devil model. The observational model represents a two-cell structure which also appears to exist in other atmospheric vortices, such as the tornado and hurricane and some laboratory and theoretical vortex models.

Singer, B. A. and Banks, D. C.

"A PREDICTOR-CORRECTOR SCHEME FOR VORTEX IDENTIFICATION"

NASA CR-194882, ICASE Report No. 94-11, May 1994, Institute for Computer Applications in Science and Engineering, NASA Langley Research Center, Hampton, VA

A new algorithm for identifying and characterizing vortices in complex flows is presented. The scheme uses both the vorticity and pressure fields. A skeleton line along the center of a vortex is produced by a two-step predictor-corrector scheme. The technique uses the vector field to move in the direction of the skeleton line and the scalar field to correct the location in the plane perpendicular to the skeleton line. A general vortex cross section can be concisely defined with five parameters at each point along the skeleton line. The details of the method and examples of its use are discussed.

Singh, J.

"AN ENHANCED SIMPLIFIED ZONAL APPROACH FOR UNSTEADY AERODYNAMICS OF NONRIGID BODIES"

AIAA Paper No. 1995-1557, Clearwater Beach, FL, May 1995

Unsteady aerodynamics of bodies undergoing time-dependent deformations is of interest to the aerodynamicist. To address this, a simplified zonal approach was developed in a previous effort to evaluate unsteady aerodynamic forces for nonrigid bodies undergoing time-dependent deformations. In the present study, this approach is enhanced to better handle arbitrary two-dimensional bodies using a robust numerical conformal transformation. The enhanced simplified zonal approach gives explicit expressions for the surface vortex sheet strength signifying vorticity content of boundary layer. Using a viscous theory of aerodynamic forces, contributions from various flow subsystems to unsteady aerodynamic force are identified. Thus, this method offers much needed physical insights into generation of and major contributions to unsteady aerodynamic forces for airfoils undergoing prescribed time-dependent deformations.

Singh, P. I. and Uberoi, M. S.

"EXPERIMENTS ON VORTEX STABILITY"

Physics of Fluids, Vol. 19, No. 12, December 1976, pp. 1858-1863

The tip vortex of a laminar flow wing was studied at a sectional lift-to-drag ratio of 60. The vortex Reynolds number was $7.8 \times 10,000$. At and near the wing the vortex core was turbulent with an axial jet. Downstream of the wing the jet rapidly dissipated and a wake developed in the core and intensity of turbulent velocities decreased. From 13 to 40 chord length periodic oscillations dominated the velocity fluctuations with little background turbulence. These instabilities had a symmetric and a helical mode with wavelength of the same order as the core diameter. In this range of distances along the vortex core the maximum axial, swirl, and fluctuating velocities vary slowly. At 40 chord lengths behind the wing there is a rapid change in these velocities. This change of state of the vortex core is

accompanied by change of velocity fluctuations from periodic to turbulent. The core showed spatial excursions. Measurements up to 80 chord lengths downstream showed no self-similar decay.

Singh, S. P., Singh, J., Stallings, J., Burgess, G. and Saha, K.

"MEASUREMENT AND ANALYSIS OF TEMPERATURE AND PRESSURE IN HIGH ALTITUDE AIR SHIPMENTS"

Packaging Technology and Science, Vol. 23, 2010, pp. 35-46.

This study was performed (at the request of the FAA) to measure temperature and pressure conditions observed by standard packages in the FedEx 'Next Day Air' network and the environmental conditions of passenger aircraft. To measure the single parcel environment, two destinations known to be served by non-pressurized feeder and pressurized aircrafts in the USA, San Luis Obispo, California, and Twin Falls, Idaho, were used to represent higher altitude paths. Test packages (0.30 x 0.30 x 0.30 m) containing one Madge Tech PRTempl 10 recorder were shipped Priority Overnight by FedEx from East Lansing, Michigan. For 6 weeks, two test packages were shipped to each destination. To measure the passenger aircraft environment, test packages (0.14 x 0.11 x 0.06 m) were both carried in the passenger cabin and checked with luggage. Results show temperature ranges, pressure drop rates, and maximum altitudes observed from 52 flights (17 feeder aircrafts) in the FedEx environment and from eight commercial passenger flights. This study compares these results with the ASTM D6653-01 test procedure with respect to suggested test pressure, pressure change, temperature, and test duration.

Sinha, A. N.

"USE OF MULTIPLE GLIDE SLOPE ANGLES"

WP-79W00278, May 1979, Mitre Corp., McLean, VA

There has been renewed interest in the use of multiple glide slopes for vortex avoidance with the development of microwave landing systems. Three concepts of multiple glide slope use are proposed and analyzed from navigation error, vortex safety and capacity benefit aspects. The results of this analysis are to be considered as preliminary findings. The primary purpose of this report is to consolidate some of the recent work in this area and present a unified talking paper as a base for further discussion and research. As a result, the paper draws heavily on the work of others - the major ones being reproduced as appendices for ready reference.

Sinha, N. K. and Ananthkrishnan, N.

"MAXIMUM STEADY ROLL RATE IN ZERO-SIDESLIP ROLL MANEUVERS OF AIRCRAFT"

Journal of Aircraft, Vol. 39, No. 5, 2002, pp. 897-899.

The maximum steady roll rate in a zero-sideslip roll maneuver has been computed using the newly developed EBA (extended bifurcation analysis) procedure. It is shown that the maximum value of the

roll rate is limited by roll coupling instabilities and is marked by a trans critical bifurcation point where the zero-sideslip states lose stability.

Sipp, D. and Jacquin, L.

"WIDNALL INSTABILITIES IN VORTEX PAIRS"

Physics of Fluids, Vol. 15, No. 7, July 2003, pp. 1861-1874

In this article we analyze the cooperative three-dimensional short-wave instabilities developing on concentrated vortex dipoles that have been obtained by means of two-dimensional direct numerical simulations. These dipoles are characterized by their aspect ratio a/b where a is the radius of the vortices based on the polar moments of vorticity and b is the separation between the vortex centroids. In the inviscid case, we show that the selection of the antisymmetric eigenmode smoothly increases with a/b : for $a/b = 0.208$, the amplification rate of the antisymmetric eigenmode is only 1.4% larger than the amplification rate of the symmetric eigenmode. When $a/b = 0.288$, this difference increases up to 7%. The results of the normal mode analysis may be compared to those of an asymptotic stability analysis of a Lamb-Oseen vortex subjected to a weak straining field, following Moore and Saffman [Proc. R. Soc. London, Ser. A 346, 413 (1975)]. This theory shows that the instability may occur whenever two Kelvin waves exist with the same frequency ω , the same axial wavenumber k and with azimuthal wavenumbers m and $m + 2$. Contrary to the case of a Rankine vortex [Tsai and Widnall, J. Fluid Mech. 73, 721 (1976)], the presence of critical layers in a Lamb-Oseen vortex prevents many possible resonances. For example, resonances between $m = -2$ and $m = 0$ modes lead to damped modes. The only resonances that occur are related to the stationary ($\omega = 0$) bending waves ($m = \pm 1$) obtained for specific values of the axial wavenumber. All these predictions are found to be in good agreement with the results obtained by the stability analysis of the considered vortex pairs. At last, we present a nonautonomous amplitude equation which considers all effects of viscosity, i.e., the viscous damping of the amplification rate of the perturbation but also the increase of the dipole aspect ratio a/b due to the viscous diffusion of the basic flowfield. The low-Reynolds number experiment of Leweke and Williamson [J. Fluid Mech. 360, 85 (1998)] is revisited under the light of these theoretical results. We show that these theoretical results yield predictions for the amplification rate and for the wavenumber that agree with the experimental observations.

Sipp, D. and Jacquin, L.

"A CRITERION OF CENTRIFUGAL INSTABILITIES IN ROTATING SYSTEMS"

Lectures in Physics, Vol. 555, 2000, pp. 299-308

This article deals with the stability of incompressible inviscid 2D planar flows in a rotating frame. We give a sufficient condition for such flows to undergo 3D short-wave centrifugal-type instabilities. If this condition is satisfied then the flow is unstable to short-wavelength perturbations. When the streamlines are closed, it is further shown that a localized unstable normal mode can be constructed in the vicinity of a streamline.

Sipp, D., Coppens, F. and Jacquin, L.

"THEORETICAL AND NUMERICAL ANALYSIS OF WAKE VORTICES"

Proceedings of 3rd International Workshop on Vortex Flows and Related Numerical Methods, ESAIM, Vol. 7, 1999, pp. 397-407

The first part of the paper analyses the linear dynamics of a vortex pair thanks to a normal mode analysis. The basic flow is a superposition of two Lamb-Oseen vortices of radius a and distance b . The long-wave Crow instability and the short-wave Widnall instabilities are fully characterized for different aspect ratios a/b of the vortex pair. In particular, as a/b increases, it is shown that the antisymmetric Widnall instabilities are favored for short-wave perturbations. This constitutes an explanation for the results obtained by Leweke & Williamson (1998). The second part of the paper deals with turbulence in the Batchelor vortex. A 3D Large Eddy Simulation (LES) shows that, starting from a linearly unstable wake-type vortex, high levels of turbulence can be obtained. But, the mean-flow then rapidly evolves towards a stable state.

Sipp, D., Coppens, F. and Jacquin, L.

"THEORETICAL AND NUMERICAL ANALYSIS OF VORTEX WAKE VORTICES"

Third International Workshop on Vortex Flows and Related Numerical Methods, ONERA, TP No. 1998-160, Toulouse, France, August 1998

This paper analyzes some linear and nonlinear properties of the dynamics of vortices. Two problems are discussed. The first concerns the linear dynamics of two Lamb-Oseen vortices. The second deals with the turbulence effects on a Batchelor-type vortex. These constitute two different aspects of the general airplane vortex wake hazard problem. The linear stability of two counter-rotating vortices, including the (long-wave) Crow instability (Crow, 1970) and the (short-wave) Widnall instability (Tsai and Widnall, 1976, and Moore and Saffman, 1975), may contribute to an aircraft vortex wake dispersion. In the present paper, these two instabilities are fully characterized in a unified frame by means of a normal mode analysis. The development of turbulence and its impact on aircraft vortices is still a matter of question. A temporal numerical simulation of an unstable Batchelor vortex is performed in order to get an insight into this problem. The first part of this paper is devoted to the linear dynamics. We first obtain the bending wave oscillation frequencies of a single Lamb-Oseen vortex by means of a shooting method. It is shown that a single Lamb-Oseen vortex is stable. Then, a spectral collocation and matrix eigenvalue method is used to analyze the dynamics of a vortex pair. In particular, the Crow instability in the long-wave limit and the Widnall instabilities are recovered by this general method. We also prove that increasing the core radius makes the interaction between the two vortices stronger. It is shown, for example, that the antisymmetric mode of the Widnall instability is promoted as the core radius increases. The second part deals with turbulence in the Batchelor vortex. It is shown that high levels of turbulence can be obtained in the vortex. Starting from a linearly unstable wake-type vortex, the mean flow evolves towards a stable state through an increase of its axial momentum. This is in accordance with the results of Ragab and Sreedhar (1995).

Sipp, D., Fabre, D., Michelin, S. and Jacquin, L.

"STABILITY OF A VORTEX WITH A HEAVY CORE"

J. Fluid Mech., Vol. 526, 2005, pp. 67-76

This paper examines the stability of swirling flows in a non-homogeneous fluid. Density gradients are shown to produce two distinct kinds of instability. The first is the centrifugal instability (CTI) which mainly affects axisymmetric, short-axial wavelength eigenmodes. The second is the Rayleigh-Taylor instability (RTI) which mainly affects non-axisymmetric, two dimensional eigenmodes. These instabilities are described for a family of model flows for which the velocity law corresponds to a Gaussian vortex with radius 1, and the density law corresponds to a Gaussian distribution characterized by a density contrast C and a characteristic radius b . A full map in the (C, b) -plane is given for the amplification rate and the structure of the most amplified eigenmode. For small density contrasts, the CTI occurs only for $b > 1$ and the RTI for b less than or equal to 0.8. On the other hand, for high density contrasts, a competition between the two kinds of instabilities is observed. From a fundamental point of view, the nature of the instability depends on the local values. This asymptotic analysis confirms that shear has a stabilizing effect on RTI and that this instability is strictly analogous to the standard RTI obtained in the case where light fluid is situated below heavier fluid in the presence of gravity.

Sipp, D., Jacquin, L. and Sagaut, P.

"A DIRECT NUMERICAL SIMULATION OF A SINUSOIDAL INSTABILITY"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 19-1 to 19-9

We present the results of a direct temporal simulation of a sinusoidal instability which developed in an eddy path that was composed of two, counter-rotating eddies. The results compare to the theory of linear instability developed by Crow. In particular, we studied the effect of grid density, limiting conditions, and the form of the initial perturbation with regards to the quality of the solution. [In French.]

Sitaraman, J. and Baeder, J. D.

"COMPUTATIONAL-FLUID-DYNAMICS-BASED ENHANCED INDICIAL AERODYNAMIC MODELS"

Journal of Aircraft, Vol. 41, No. 4, July-August 2004, pp. 798-810

Direct Euler calculations were performed to verify the accuracy of linearized airload models and to generate a numerical database for the determination of generalized sharp-edged vertical gust response functions. The field velocity approach was used in the computational fluid dynamics (CFD) code to incorporate the impulsive boundary conditions that were characteristic of the problems studied. Linearized airload models were constructed in three dimensions by coupling the indicial models

obtained in two dimensions with a Weissinger-L vortex panel method. The vortex panel method was suitably modified to include the shed near wake effects and impulsive boundary conditions. Studies conducted on step change in angle of attack and step change in pitch rate for a finite wing showed that the linearized models are sufficiently accurate in predicting the section wise air loads. Generalized gust functions were determined with a constrained minimization of least-square error with a CFD-generated database. Studies on airfoil vortex interaction and parallel blade vortex interaction showed excellent correlation of results from linearized aerodynamic model with the corresponding CFD calculations for both lift and pitching moment response. Overall, the linearized methods were found to produce sufficiently accurate results compared to CFD calculations, taking about four orders of magnitude less computational time.

Sitaraman, J., Potsdam, M., Wissink, A., Jayaraman, B., Datta, A., Mavriplis, D. and Saberi, H.

"ROTOR LOADS PREDICTION USING HELIOS: A MULTISOLVER FRAMEWORK FOR ROTORCRAFT AEROMECHANICS ANALYSIS"

Journal of Aircraft, Vol. 50, No. 2, March-April 2013, pp. 478-492.

This paper documents the prediction of UH-60A Black Hawk aerodynamic loading using the multisolver Computational Fluid Dynamics/Computational Structural Dynamics analysis framework for rotorcraft Helios for a range of critical steady forward flight conditions. Comparisons with available flight test data are provided for all the predictions. The Helios framework combines multiple solvers and multiple grid paradigms (unstructured and adaptive Cartesian) such that the advantages of each paradigm is preserved. Further, the software is highly automated for execution and designed in a modular fashion to minimize the burden on both the users and developers. The technical approach presented herein provides details of all the participant modules and the interfaces used for their integration into the software framework. The results composed of sectional aerodynamic loading and wake visualizations are presented. Solution-based adaptive mesh refinement, a salient feature of the Helios framework, is explored for all flight conditions and comparisons are provided for both aerodynamic loading and vortex wake structure with and without adaptive mesh refinement.

Sjoholm, M., Angelou, N., Hansen, P., Hansen, K. H., Mikkelsen, T. K., Haga, S., Silgjerd, J. A. and Starsmore, N.

"HELICOPTER DOWNWASH MEASURED BY CONTINUOUS-WAVE DOPPLER LIDARS WITH AGILE BEAM STEERING"

16th International Symposium for the Advancement of Boundary-Layer Remote Sensing, June 2012, Boulder, CO, Poster Session 2, pp. 267-270.

A ground-based remote sensing short-range WindScanner with agile beam steering based on a modified ZephIR continuous-wave wind lidar (Light Detection And Ranging) and a double prism arrangement has recently been developed at the Department of Wind Energy at the DTU Riso campus. The WindScanner measures the line-of-sight component of the wind and by rapid steering of the line-

of-sight and the focus position, all locations within a cone with a full top angle of 120 degrees can be reached from about 8 meters out to some hundred meters depending on the range resolution needed. By using three such WindScanners, all three components of the wind can be retrieved. Here, the first mean 2D turbulent wind fields measured in a horizontal and a vertical plane below a hovering search and rescue helicopter are presented. The line-of-sights of two synchronized WindScanners were scanned within the plane of interest. Since both line-of-sights always were inside the plane scanned, the influence of the wind component perpendicular to the plane was avoided. The results indicate that the flow field below a helicopter can be characterized remotely, which can support helicopter optimization regarding, for example, minimizing the risk to aircraft and personnel when operating in a search and rescue role. The results from the application of the short-range WindScanner technology to the complex and turbulent helicopter downwash demonstrates the possibilities also within less demanding flows encountered within complex terrain and wind energy related research for which the WindScanner technology primarily has been developed.

Sjöholm, M., Angelou, N., Hansen, P., Hansen, K. H., Mikkelsen, T., Haga, S., Silgjerd, J. A. and Starsmore, N.

"TWO-DIMENSIONAL ROTORCRAFT DOWNWASH FLOW FIELD MEASUREMENTS BY LIDAR-BASED WIND SCANNERS WITH AGILE BEAM STEERING"

Journal of Atmospheric and Oceanic Technology, Vol. 31, April 2014, pp. 930-937.

A major risk to helicopters is the unexpected encounter of degraded visual environments in close-to-ground operations, where a loss of visibility often is caused by clouds of dust (brownout) stirred up by intense downwash. The understanding of the phenomenon is limited, and there is a need for instruments that can measure flow fields on scales larger than a few meters with good resolution. This paper reports on the use of synchronized continuous-wave Doppler lidars for rotorcraft downwash flow field studies. Built from a modified ZephIR wind lidar and a double-prism arrangement for agile beam steering, a wind scanner -- WindScanner -- has been developed at the Department of Wind Energy at the Technical University of Denmark Riso campus. The WindScanner measures the line-of-sight component of the airflow remotely and by rapid steering, the line-of-sight direction, and the focus position; all points in space within a cone with a full opening angle of 120 degrees can be reached from about 8 m out to some hundred meters depending on the range resolution required. The first two-dimensional mean wind fields measured in a horizontal plane and in a vertical plane below a hovering search and rescue helicopter are presented. Since the line-of-sight directions of the two synchronized WindScanners were scanned within the plane of interest, the influence of the wind component perpendicular to the plane was avoided. The results also demonstrate the possibilities within less demanding flows encountered within complex terrain and wind-energy-related research for which the WindScanner technology primarily has been developed.

Skoog, R. B.

"A COMPARISON OF TWO FLIGHT-TEST PROCEDURES FOR THE DETERMINATION OF AILERON CONTROL CAPABILITIES OF AN AIRPLANE"

NACA Report 5E22, July 1945, Ames Aeronautical Laboratory, Moffett Field, CA.

A comparison, based on actual flight tests of several airplanes, has been made between two flight-test procedures for the determination of the aileron control capabilities of an airplane. The procedures consist of performing rudder-fixed aileron rolls from straight unbanked flight and from steady turning flight. For the airplanes considered in this report, no significant difference was found to exist in the index of aileron power $p_b/2V$ as determined from data taken with either of the testing methods. This agreement was confirmed as being correct in a comparison of sideslip angle occurring at the time of maximum rate of roll. Extension of the close agreement shown in the report to cover all other present-day airplanes is believed to be reasonable.

Skully, M. P.

"A METHOD OF COMPUTING HELICOPTER VORTEX WAKE DISTORTION"

Report ASRL 138-1, June 1967, Massachusetts Institute of Technology, Cambridge MA.

A method of computing the geometry of the tip vortex of a helicopter rotor in steady, forward flight, including the distortion due to the velocities induced by the vortex wake, has been developed. The relative importance of various parameters and approximations used by this method has been evaluated for one test case., including comparison with experimental results obtained from a flow visualization study.

Slaboch, P. E.

"AN OPERATIONAL MODEL FOR THE PREDICTION OF JET BLAST"

AIAA Paper No. 2012-1229, January 2012, Nashville, Tennessee.

This paper presents an operational model for the prediction of jet blast. The model was developed based upon three modules including a jet exhaust model, jet centerline decay model and aircraft motion model. The final analysis was compared with data acquired during a jet blast study conducted by the Volpe Center in 1999. The current analysis closely matched the data from the 1999 test. The analysis was then used to predict the jet blast evolution from aircraft that have been introduced since 1999, including the Boeing 777-300ER. The result of this analysis is a tool that can be used to help provide insight to operating procedure designs where jet blast concerns may arise.

Slattery, R. A. and Cheng, V. H. L.

"SENSITIVITY OF EN-ROUTE SCHEDULING TO VARIABLE SEPARATION IN THE TERMINAL AREA"

AIAA Paper No. 1997-3736, Reston, VA, August 1997

NASA is developing a system that can provide dynamic wake vortex separation criteria by predicting the decay and transport of the vortices in various atmospheric conditions. Varying separation affects aircraft throughout the airspace, and the wake vortex system should be designed not to cause the controllers to continuously replan. Stability is defined as producing delays that can be absorbed solely by aircraft close to landing, instead affecting aircraft in a larger airspace. This paper examines the stability of the wake vortex system by way of parametric study. The parameters are the frequency and size of the separation changes, and their probability distributions. The transient behavior of the system delay under changing separation is examined; it is shown that for the same time, reductions in separation have a larger effect than increases. A linear relationship between the parameters producing a stable delay profile is calculated for the assumed probability distributions.

Sloof, J. W., de Wolf, W. B., van der Wal, H. M. M. and Maseland, J. E. J.

"AERODYNAMIC AND AERO-ACOUSTIC EFFECTS OF FLAP TIP FENCES, "

AIAA Paper No. 2002-0848, Reno, NV, January 200.

The application of winglet or end-plate type devices to the tips of the trailing-edge flap of a wing has, for some time, been suggested as a (potential) means for improving the aerodynamic efficiency during take-off/climb and for decreasing the airframe noise of transport aircraft in the approach/landing configuration. A third aspect of the application of such devices is their possible effect on the wake vortex characteristics. In this paper the main results and conclusions are presented of exploratory CFD simulations and low-speed wind tunnel tests on a half model of a civil transport type of aircraft configuration with trailing-edge flaps extended and with (and without) winglet type 'fences' attached to the main wing at the position of the outboard tip of the trailing-edge flap. Both take-off/climb and approach/landing flap settings were tested. The main results of the investigation are that the application of flap tip fences may lead to: a substantial (up to 7 dB) reduction of the noise source level of the flap tip in the approaching/landing configuration (about equal for the lower and the upper + lower fence configurations), a (small) improvement of L/D and C_{lmax} in take-off/climb of up to 1% (lower fence only), and possibly a small reduction of a few percent of the strength of the wake vortex from the flap tip region.

Slooff, J. W., de Wolf, W. B., van der Wal, H. M. M. and Maseland, J. E. J.

"AERODYNAMIC AND AERO-ACOUSTIC EFFECTS OF FLAP TIP FENCES"

AIAA Paper No. 2002-0848, Reno, NV, Jan. 2002

The application of winglet or end-plate type devices to the tips of the trailing-edge flap of a wing has, for some time, been suggested as a (potential) means for improving the aerodynamic efficiency during take-off/climb and for decreasing the airframe noise of transport aircraft in the approach/landing configuration. A third aspect of the application of such devices is their possible effect on the wake vortex characteristics. In this paper the main results and conclusions are presented of exploratory CFD simulations and low-speed wind tunnel tests on a half model of a civil transport type of aircraft

configuration with trailing-edge flaps extended and with (and without) winglet type 'fences' attached to the main wing at the position of the outboard tip of the trailing-edge flap. Application of flap tip fences may lead to a small reduction of a few percent of the strength of the wake vortex from the flap tip region.

Slotnick, J. P., An, M. Y., Mysko, S. J., Yeh, D. T., Roth, K., Rogers, S. E., Nash, S. M. and Baker, M. D.

"NAVIER-STOKES ANALYSIS OF A HIGH WING TRANSPORT HIGH-LIFT CONFIGURATION WITH EXTERNALLY BLOWN FLAPS"

AIAA Paper No. 2000-4219, Denver, CO, August 2000

This paper gives an overview of the numerical simulation of the complete 3D High Wing Transport landing configuration using Reynolds-Averaged Navier-Stokes methods. Rather than concentrating on the numerical details of the CFD simulations themselves, an assessment of the predictive capability of the computational method relative to test data is emphasized. Several technical issues, including test facility wall interference effects and jet modeling effects, are presented in detail. The application of the computational method to study nacelle strake effectiveness and wake vortex prediction is also highlighted.

Smalikho, I. and Banakh, V.

"INVESTIGATION OF FEASIBILITY OF WIND TURBULENCE MEASUREMENT BY A PULSED COHERENT DOPPLER LIDAR IN THE ATMOSPHERIC BOUNDARY LAYER"

28th International Laser Radar Conference, June 2017, Bucharest, Romania, published in EPJ Web of Conferences, Vol. 176, 2018, pp. 06016-1 to 06016-4.

Feasibilities of determination of the wind turbulence parameters from data measured by the Stream Line coherent Doppler lidar under different atmospheric conditions have been studied experimentally. It has been found that the spatial structure of the turbulence is described well by the von Karman model in the layer of intensive mixing. From the lidar measurements at night under stable conditions the estimation of the outer scale of turbulence with the use of the von Karman model is not possible.

Smalikho, I. N.

"ACCURACY OF THE TURBULENT ENERGY DISSIPATION RATE ESTIMATION FROM THE TEMPORAL SPECTRUM OF WIND VELOCITY FLUCTUATIONS"

Atmospheric and Oceanic Optics, Vol. 10, No. 8, August 1997, pp. 559-563.

This paper describes the errors in the estimates of the turbulent energy dissipation rate based on the likelihood maximum from time spectra of wind velocity measured with an acoustic anemometer and a Doppler lidar.

Smalikho, I. N.

"ON MEASUREMENT OF THE DISSIPATION RATE OF THE TURBULENT ENERGY WITH A CW DOPPLER LIDAR"

Atmospheric and Oceanic Optics, Vol. 8, No. 10, October 1995, pp. 788-793.

Various methods of measurement of the dissipation rate of the turbulent energy by means of a cw Doppler lidar are analyzed in the paper. It is shown that information on the dissipation rate can be derived from the structure function or the spectrum of wind velocity measured with Doppler lidar having arbitrary length of a sounded volume.

Smalikho, I. N. and Banakh, V. A.

"ESTIMATION OF AIRCRAFT WAKE VORTEX PARAMETERS FROM DATA MEASURED WITH A 1.5-MICRON COHERENT DOPPLER LIDAR"

Optics Letters, Vol. 40, No. 14, July 2015, pp. 3408-3411.

A strategy of measurement by a 1.5-micron pulsed coherent Doppler lidar 'Stream Line' has been developed, and a method for estimation of aircraft wake vortices from the lidar data has been proposed. The principal possibility of obtaining the information about the vortex situation over an airport airfield with the Stream-Line lidar has been demonstrated.

Smalikho, I. N. and Banakh, V. A.

"ESTIMATION OF AIRCRAFT WAKE VORTEX PARAMETERS FROM DATA MEASURED BY A STREAM LINE LIDAR"

XXI International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, November 2015, Tomsk, Russian Federation, Proceedings of SPIE, Vol. 9680, pp. 968037-1 to 968037-7.

A method for estimation of aircraft wake vortex parameters (coordinates of axis and circulation of vortices) from raw data measured by a pulsed coherent Doppler lidar 'Stream Line' has been offered. By numerical simulation we found optimal measurement parameters, with which it is possible to obtain information about the wake vortices, despite the low level of echo signal inherent to this lidar. The method was tested in an experiment at the airfield of Tomsk airport. The results of the experimental data processing are consistent with theoretical calculations for the type of aircrafts involved in this experiment.

Smalikho, I. N. and Rahm, S.

"LIDAR INVESTIGATIONS OF THE EFFECTS OF WIND AND ATMOSPHERIC TURBULENCE ON AN AIRCRAFT WAKE VORTEX"

Atmospheric and Oceanic Optics, Vol. 23, No. 2, 2010, pp. 137-146.

The effects of wind and atmospheric turbulence on an aircraft wake vortex are studied experimentally. A 2-micron coherent Doppler lidar is used for measuring the parameters of the aircraft vortices, wind, and turbulence. The results are presented of lidar measurements of aircraft vortex parameters at different wind velocities and turbulence levels. An empirical dependence of the aircraft vortex lifespan on the dissipation rate of atmospheric turbulence energy has been obtained from the experimental data for the first time.

Smalikho, I. N., Banakh, V. A. and Falits, A. V.

"INVESTIGATION OF FEASIBILITIES OF AIRCRAFT WAKE VORTEX MEASUREMENT BY A LOW-ENERGY 1.5-MICRON PULSED COHERENT DOPPLER LIDAR"

18th Coherent Laser Radar Conference, June 2016, Boulder, CO.

In this work the feasibilities of the extraction of information about aircraft wake vortices from data measured by a low-energy 1.5-micron pulsed coherent Doppler lidar (PCDL) are investigated. A strategy of measurement by such lidar at airfield of an airport has been developed and the conditions of applicability of the lidar for wake vortex measurement have been determined. The applicability of the 1.5-micron Stream Line PCDL for measurements of the wake vortices generated by a landing aircraft has been demonstrated in the experiments carried out at the airfield of the Tolmachevo Airport. We estimated parameters of the wake vortices for aircrafts of various types, including Boeing-747 cargo aircraft.

Smalikho, I. N., Banakh, V. A. and Falits, A. V.

"MEASUREMENTS OF AIRCRAFT WAKE VORTEX PARAMETERS BY A STREAM LINE DOPPLER LIDAR"

Atmospheric and Oceanic Optics, Vol. 30, No. 6, 2017, pp. 588-595.

Results of measurements of the parameters of aircraft wake vortices by a Stream Line coherent Doppler lidar during the three-day experiment on the airfield of Tolmachevo Airport are presented. The spatial dynamics and evolution of the wake vortices generated by landing aircraft of different types, from Airbus A319 passenger aircraft to heavy Boeing 747-8 cargo aircraft, are analyzed. It is shown that Stream Line lidars may be used to receive reliable information about the presence and intensity of aircraft wake vortices in the vicinity of a runway.

Smalikho, I. N., Banakh, V. A., Holzaepfel, F. and Rahm, S.

"METHOD OF RADIAL VELOCITIES FOR THE ESTIMATION OF AIRCRAFT WAKE VORTEX PARAMETERS FROM DATA MEASURED BY COHERENT DOPPLER LIDAR"

1990

Optics Express, Vol. 23, No. 19, September 2015, pp. A1194-A1207.

The method of radial velocities (RV) is applied to estimate aircraft wake vortex parameters from measurements conducted with pulsed coherent Doppler lidar (PCDL). Operations of the Stream Line lidar and the 2-micron PCDL are simulated numerically to analyze the accuracy of the estimated wake vortex parameters with the RV method. The RV method is also used to estimate wake vortex trajectories and circulation from lidar measurements at Tomsk and Munich airports. The method of velocity envelopes and the RV method are compared employing data gathered with the 2-micron PCDL. The domain of applicability of the RV method is determined.

Smalikho, I. N., Banakh, V. A., Pichugina, Y. L., Brewer, W. A., Banta, R. M., Lundquist, J. K. and Kelley, N. D.

"LIDAR INVESTIGATION OF ATMOSPHERE EFFECT ON A WIND TURBINE WAKE"

Journal of Atmospheric and Oceanic Technology, Vol. 30, November 2013, pp. 2554-2570.

An experimental study of the spatial wind structure in the vicinity of a wind turbine by a NOAA coherent Doppler lidar has been conducted. It was found that a working wind turbine generates a wake with the maximum velocity deficit varying from 27 to 74 percent and with the longitudinal dimension varying from 120 up to 1180m, depending on the wind strength and atmospheric turbulence. It is shown that, at high wind speeds, the twofold increase of the turbulent energy dissipation rate (from 0.0066 to 0.013 (meter squared)/(second cubed)) leads, on average, to halving of the longitudinal dimension of the wind turbine wake (from 680 to 340m).

Smalikho, I., Kopp, F. and Rahm, S.

"MEASUREMENT OF ATMOSPHERIC TURBULENCE BY 2-MICRON DOPPLER LIDAR"

Journal of Atmospheric and Oceanic Technology, Vol. 22, No. 5, November 2005, pp. 1733-1747.

Two methods for the estimation of the turbulence energy dissipation rate (TEDR) from data measured by a 2-micron coherent Doppler lidar are described in this paper. Based on data measured at the Tarbes-Lourdes-Pyrenees International Airport in summer 2003, height profiles of TEDR have been retrieved. The results of TEDR estimation both from the Doppler spectrum width and from the velocity structure function are compared. Moreover, the experiment has been treated by numerical simulation and the theoretical results have been used for verification of the described methods.

Smart, M. K. and Kalkhoran, I. M.

"EFFECT OF SHOCK STRENGTH ON OBLIQUE SHOCK-WAVE/VORTEX INTERACTION"

AIAA Journal, Vol. 33, No. 11, November 1995, pp. 2137-2143

An experimental study of the interaction between streamwise vortices and two-dimensional oblique shock waves has been conducted at Mach 2.5. The experiments involved positioning an instrumented two-dimensional wedge downstream of a semispan wing so that the trailing tip vortex from the wing interacted with the oblique shock wave formed over the wedge surface. The experiments were designed to simulate interaction of streamwise vortices with shock waves formed over aerodynamic surfaces or in supersonic inlets. The influence of oblique shock wave intensity on this inherently three-dimensional interaction was examined for vortices of variable strength. Results indicate that the interaction of a moderate strength vortex with an oblique shock wave can lead to the formation of a steady separated shock structure upstream of the oblique shock front. A significant expansion of the vortex core is observed in these cases, and the scale of the structure increases with shock wave intensity. In some instances, the separated shock structure continues through the oblique shock front to strike the shock-generating wedge forming a three-dimensional shock-wave/boundary-layer interaction. The experiments indicate that significant distortion of streamwise vortices can be precipitated by oblique shock fronts with supersonic downstream conditions.

Smart, M. K. and Kalkhoran, I. M.

"FLOW MODEL FOR PREDICTING NORMAL SHOCK WAVE INDUCED VORTEX BREAKDOWN"

AIAA Journal, Vol. 35, No. 10, October 1997, pp. 1589-1596

An analytical study of normal shock wave induced vortex breakdown has been undertaken. In this inviscid axisymmetric analysis, the response of supersonic streamwise vortices to imposed normal shocks has been determined by modeling the rotational core of the vortex as a slender, swirling layer. For vortex/shock combinations of increasing strength, the analysis predicts an ever-increasing axial velocity deficit in the vortex core. Vortex breakdown is presumed to occur if a vortex/shock combination leads to flow stagnation at the vortex axis. The results of this study indicate that an inverse relationship exists between vortex swirl and freestream Mach number at breakdown. The breakdown limit curve generated using this analysis shows good correlation with established experimental results, indicating that the onset of normal shock wave induced vortex breakdown can be predicted with a relatively simple flow model and without recourse to numerical simulation. Interpretation of some normal shock wave/vortex interaction experiments in light of the predictions suggests that the phenomenon previously known as supersonic vortex distortion is a form of vortex breakdown.

Smart, M. K. and Kalkhoran, I. M.

"A SCENARIO FOR OBLIQUE SHOCK WAVE INDUCED VORTEX BREAKDOWN"

AIAA Paper No. 1997-0069, January 1997, Reno, NV.

Thus far the 3D nature of oblique shock wave/vortex interaction has made its measurement and analysis difficult in both experimental and numerical simulation frameworks. As an alternative, the problem has been examined here from a physically intuitive standpoint to better understand its

dominant features. This approach has enabled a fluid dynamic scenario involving supersonic vortex breakdown to be developed as an explanation for the observed flow reorganization. An approximate analysis for predicting oblique shock wave induced vortex breakdown was developed using this scenario. Results of the analysis for some experimentally investigated vortex/shock combinations indicate that the prediction of vortex breakdown corresponds closely with the appearance of a fully developed separated shock structure upstream of the original oblique shock plane. This correlation is seen as strong circumstantial evidence that vortex breakdown is responsible for the dramatic changes observed in the interaction flow fields.

Smart, M. K. and Kalkhoran, I. M.

"THE EFFECT OF SHOCK STRENGTH ON OBLIQUE SHOCK WAVE-VORTEX INTERACTION"

AIAA Paper No. 1995-0098, January 1995, Reno, NV.

An experimental study of the interaction between streamwise vortices and two-dimensional oblique shock waves has been conducted at Mach 2.5. The experiments involved positioning an instrumented two-dimensional wedge downstream of a semi-span wing so that the trailing tip vortex from the wing interacted with the oblique shock wave formed over the wedge surface. The experiments were designed to simulate interaction of streamwise vortices with shock waves formed over aerodynamic surfaces or in supersonic inlets. The influence of oblique shock wave intensity on this inherently three-dimensional interaction was examined for vortices of variable strength. Results indicate that the interaction of a moderate strength vortex with an oblique shock wave can lead to the formation of a steady separated shock structure upstream of the oblique shock front. The scale of the structure increased with shock wave intensity and showed a close resemblance to the unsteady vortex distortion observed during the head-on interaction of streamwise vortices with a wedge leading edge reported in previous studies. In some instances, the separated shock structure was observed to continue through the oblique shock front to strike the shock generating wedge forming a three-dimensional shock wave/boundary layer interaction.

Smart, M. K., Kalkhoran, I. M. and Bentson, J.

"MEASUREMENTS OF SUPERSONIC WING TIP VORTICES"

AIAA Paper No. 1994-2576, Colorado Springs, CO, June 1994

Small-scale 4- 5-hole cone probes have been used to experimentally survey supersonic wingtip vortices at Mach 2.5, for wing angles of attack in the 5-10 deg range. The vortex core region's Mach number, flow angularity, and total pressure distribution are obtained, and the feasibility of using cone probes calibrated with a numerical flow solver is demonstrated.

Smart, M. K., Kalkhoran, I. M. and Bentson, J.

"MEASUREMENTS OF SUPERSONIC WING TIP VORTICES"

1993

AIAA Journal, Vol. 33, No. 10, October 1995, pp. 1761-1768.

An experimental study of supersonic wing tip vortices has been conducted at Mach 2.49 using small-scale four-hole and five-hole conical probes. The study was performed 2.25 chords downstream of a semispan rectangular wing at angles of attack of 5.7 and 10.4 deg. The main objective of the experiments was to determine the Mach number, flow angularity, and total pressure distribution in the core region of supersonic wing tip vortices. A secondary aim was to demonstrate the feasibility of calibrating a conical probe using a computational solution to predict the flow characteristics. Results of the present investigation showed that the numerically generated calibration data can be used for pointed nose four-hole conical probes but were not sufficiently accurate for conventional five-hole probes due to nose bluntness effects. A combination of four-hole conical probe measurements with independent pitot pressure measurements indicated a significant Mach number and total pressure deficit in the core regions of supersonic wing tip vortices, combined with an asymmetric 'Burger-like' swirl distribution.

Smart, M. K., Kalkhoran, I. M. and Popovic, S.

"SOME ASPECTS OF STREAMWISE VORTEX BEHAVIOR DURING OBLIQUE SHOCK WAVE/VORTEX INTERACTION"

Shock Waves, Vol. 8, 1998, pp. 243-255

An experimental study of the flowfield generated by the interaction of a streamwise vortex having a strong wake-type axial Mach number profile and a two-dimensional oblique shock wave was conducted in a Mach 2.49 flow. The experiments were aimed at investigating the dynamics of supersonic vortex distortion and to study downstream behavior of a streamwise vortex during a strong shock wave/vortex encounter. The experiments involved positioning an oblique shock generator in the form of a two-dimensional wedge downstream of a semi-span, vortex generator wing section so that the wing-tip vortex interacted with the otherwise planar oblique shock wave. Planar laser sheet visualizations of the flowfield indicated an expansion of the vortex core in crossing a spherically blunt-nose shock front. The maximum vortex core diameter occurred at a distance of 12.7 mm downstream of the wedge leading edge where the vortex had a core diameter of more than double its undisturbed value. At distances further downstream the vortex core diameter remained nearly constant, while it appeared to become more diffused at distances far from the wedge leading edge. Measurements of vortex trajectory revealed that the vortex convected in the freestream direction immediately downstream of the bulged-forward shock structure, while it traveled parallel to the wedge surface at distances further downstream. The turbulent distorted vortex structure which formed because of the interaction, was found to be sensitive to downstream disturbances in a manner consistent with incompressible vortex breakdown. Physical arguments are presented to relate behavior of streamwise vortices during oblique and normal shock wave interactions.

Smith, A. P.

"USING REAL-TIME AIRCRAFT REPORTS OF WIND AND ENVIRONMENTAL PARAMETERS TO ENABLE DYNAMIC COCKPIT-BASED WAKE TOOLS"

ICNS 2011 Renovating the Global Air Transportation System, May 2011, Herndon, VA.

The FAA is implementing the NextGen in the US NAS. The MITRE Corp. is supporting the FAA in this mission, and conducts research activities that assist the FAA in leveraging emerging aircraft capabilities. A key area is evaluating the feasibility of delegating longitudinal aircraft spacing to pilots even during low visibility conditions. As longitudinal spacing is delegated to the flight crew, flight-deck based tools are needed to support the task. To make a realistic assessment of the location and strength of a wake vortex, real-time weather information needs to be known in the vicinity of the aircraft producing the wake. This paper addresses the quality of that information and how any uncertainty in this information will affect the estimate of the location and strength of wake using current wake dynamics estimating programs that could be used on an aircraft. Using MDCRS data, we have found that there is uncertainty in wind and other atmospheric parameters, even in the approach phase of flight, over a short span of time. Using these results, we show the uncertainty in the wake positions and discuss the implications for using this information for cockpit visualization tools.

Smith, A., Lott, N. and Vose, R.

"THE INTEGRATED SURFACE DATABASE: RECENT DEVELOPMENTS AND PARTNERSHIPS"

Bulletin of the American Meteorological Society, vol. 92, issue 6, June 2011, pp. 704-708

This paper describes a dataset containing data from more than 100 original data sources that collectively archived hundreds of meteorological variables. The primary data sources include the Automated Surface Observing System (ASOS), Automated Weather Observing System (AWOS), Synoptic, Airways, METAR, Coastal Marine (CMAN), Buoy, and various others, from both military and civilian stations including both automated and manual observations. Summary of daily parameters such as maximum/minimum temperature, 24-h precipitation, and snow depth are also included in ISD, to the extent that they are reported in the hourly data sources. Furthermore, this paper describes Quality Control, Examples Research and Industry, Recent Plans, and Data Access and Products.

Smith, B. E. and Ross, J. C.

"APPLICATION OF PANEL METHOD TO WAKE VORTEX/WING INTERACTION AND COMPARISON WITH EXPERIMENTAL DATA"

NASA TM-88337, September 1987, NASA Ames Research Center, Moffett Field, CA

The ability of the Vortex Separation AEROdynamics (VSAERO) program to calculate aerodynamic loads on wings due to interaction with free vortices was studied. The loads were calculated for various positions of a downstream following wing relative to an upstream vortex-generating wing. Calculated vortex-induced span loads, rolling-moment coefficients, and lift coefficients on the following wing were

compared with experimental results of McMillan et al. and El-Ramly et al. Comparisons of calculated and experimental vortex tangential velocities were also made.

Smith, B. E. and Ross, J. C.

"APPLICATION OF PANEL METHOD TO WAKE VORTEX/WING INTERACTION AND COMPARISON WITH EXPERIMENT"

AIAA Paper No. 1984-2182, Seattle, WA, August 1984

The ability of a low-order panel method to calculate the aerodynamic loads on wings caused by interaction with wake vortices was studied. The loads were calculated for various positions of a downstream following wing relative to an upstream vortex-generating wing. Calculated vortex-induced span loads and rolling-moment coefficients on the following wing were compared with experimental data. A good agreement with experiment was obtained when the following wing was located more than one following-wing chord length from the tip vortex. The predictions deteriorated as the following wing was placed closer to the vortex. At large downstream distances (approximately 10 generating-wing chord lengths), induced rolling-moment coefficients on the following wing were consistently overestimated. Despite the strong interaction between the wake-vortex filaments and surface doublet panels, the accuracy of the calculations was in most cases independent of the panel distribution and density. A good agreement between theoretical and experimental loads was obtained with a minimum of experimentation with panel arrangements.

Smith, H. C.

"METHOD FOR REDUCING THE TANGENTIAL VELOCITIES IN AIRCRAFT TRAILING VORTICES"

J. Aircraft, Vol. 17, No. 12, December 1980, pp. 861-866

A method is presented to reduce the tangential velocities in the trailing vortex system shed from an airplane wing. The device employed is a porous section of the wing at the tip which essentially tends to equalize the pressure on the upper and lower surfaces. Experiments were conducted on a full-scale aircraft in flight and vorticity measured by probes devised specifically for this purpose. Results showed significant reduction in tangential velocities close behind the wing and to a lesser degree far downstream. Controllable porosity is suggested as a means of reducing the vortex tangential velocities and subsequent potential induced rolling moment imposed on a following aircraft.

Smith, H. J.

"A FLIGHT TEST INVESTIGATION OF THE ROLLING MOMENTS INDUCED ON A T-37B AIRPLANE IN THE WAKE OF A B-747 AIRPLANE"

NASA TM X-56031, April 1975, NASA Flight Research Center, Edwards, CA

A flight test investigation of the B-747 vortex wake characteristics was conducted using a T-37B as a probe aircraft. The primary purpose of the program was the validation of the results of B-747 model test which predicted significant alleviation of the vortex strength when only the inboard flaps were deflected. Measurements of the vortex-induced rolling moments of the probe aircraft showed that the predicted alleviation did occur. Unfortunately, this alleviation could not be fully realized for realistic operations: the effects of landing gear extension, increased lift coefficient, idle thrust, and side-slip were investigated, and all had an adverse effect on the alleviated condition as evidenced by increased induced rolling moments of the T-37B probe aircraft. Idle thrust also increased the strength of the B-747 wake vortices with both inboard and outboard flaps extended.

Smith, J. C.

"ANALYSIS OF WAKE VAS BENEFITS USING ACES BUILD 3.2.1"

NASA/CR-2005-213939, January 2005, Swales Aerospace, Hampton, VA

The FAA and NASA are currently engaged in a Wake Turbulence Research Program to revise wake turbulence separation standards, procedures, and criteria to increase airport capacity while maintaining or increasing safety. The research program is divided into three phases: Phase I - near term procedural enhancements; Phase II - wind dependent Wake Vortex Advisory System (WakeVAS) Concepts of Operations (ConOps); and Phase III - farther term ConOps based on wake prediction and sensing. This report contains an analysis that evaluates the benefits of a closely spaced parallel runway (CSPR) Phase I ConOps, a single runway and CSPR Phase II ConOps and a single runway Phase III ConOps. A series of simulation runs were performed using the Airspace Concepts Evaluation System (ACES) Build 3.2.1 air traffic simulator to provide an initial assessment of the reduction in delay and cost savings obtained using a WakeVAS at selected U.S. airports. The ACES simulator is being developed by NASA Ames Research Center as part of the Virtual Airspace Modelling and Simulation (VAMS) program.

Smith, J. C.

"ANALYSIS OF WAKE VAS BENEFITS USING ACES BUILD 3.2.1 - VAMS TYPE 1 ASSESSMENT"

NASA/CR-2005-213940, December 2005, Swales Aerospace, Hampton, VA

The FAA and NASA are currently engaged in a Wake Turbulence Research Program to revise wake turbulence separation standards, procedures, and criteria to increase airport capacity while maintaining or increasing safety. The research program is divided into three phases: Phase I - near term procedural enhancements; Phase II - wind dependant Wake Vortex Advisory System (WakeVAS) Concepts of Operations (ConOps); and Phase III - farther term ConOps based on wake prediction and sensing. The Phase III Wake VAS ConOps is one element of the Virtual Airspace Modelling and Simulation (VAMS) program blended concepts for enhancing the total system wide capacity of the National Airspace System (NAS). This report contains a VAMS Program Type 1 (stand-alone) assessment of the expected capacity benefits of Wake VAS at the 35 FAA Benchmark Airports and determines the

consequent reduction in delay using the Airspace Concepts Evaluation System (ACES) Build 3.2.1 simulator.

Smith, J. C. and Dollyhigh, S. M.

"WAKE VORTEX ADVISORY SYSTEM (WakeVAS) EVALUATION OF IMPACTS ON THE NATIONAL AIRSPACE SYSTEM"

NASA CR-2005-213523, January 2005, Swales Aerospace, Hampton, VA

This report is one of a series that describes an ongoing effort in high-fidelity modeling/simulation, evaluation and analysis of the benefits and performance metrics of the Wake Vortex Advisory System (WakeVAS) Concept of Operations being developed as part of the Virtual Airspace Modeling and Simulation (VAMS) project. A previous study, determined the overall increases in runway arrival rates that could be achieved at 12 selected airports due to WakeVAS reduced aircraft spacing under Instrument Meteorological Conditions. This study builds on the previous work to evaluate the NAS wide impacts of equipping various numbers of airports with WakeVAS. A queuing network model of the National Airspace System, build by the Logistics Management Institute, McLean, VA, for NASA (LMINET) was used to estimate the reduction in delay that could be achieved by using WakeVAS under non-visual meteorological conditions for the projected air traffic demand in 2010. The results from LMINET were used to estimate the total annual delay reduction that could be achieved and from this, an estimate of the air carrier variable operating cost saving was made.

Smith, J. H. B.

"VORTEX FLOWS IN AERODYNAMICS"

Annual Review Fluid Mechanics, 1986, Vol. 18, pp. 221-242

Many different vortex flows arise in the external aerodynamics of aircraft. This review has concentrated on two types of vortex flow, distinguished by their relative simplicity and their susceptibility to inviscid modeling. The relevance of Prandtl-Batchelor flows in any practical context has yet to be demonstrated, but indications of their potential usefulness justify the continuing investigation of their behavior, of the means to compute them, and of the circumstances in which they exist. The relevance of vortex flows arising from highly swept separation lines, on the other hand, is not in doubt. However, despite the many treatments developed and the numerous configurations studied, some fundamental problems remain. On the fringes of the subject lie the two principal needs: a model of secondary separation, and (relatedly) a convincing treatment of turbulent separation from a smooth surface to parallel the triple-deck treatment of laminar separation. These are needed to supplement the inviscid models. All the models suffer from weaknesses when the vortices lie close to solid surfaces: particularly the surfaces generating them, but also surfaces downstream. Yet these are often the circumstances of greatest interest when gains in aerodynamic efficiency become possible and when the most serious stability and control difficulties arise. The unsought appearance of vortices in time-marching solutions of the Euler equations is an exciting and unexpected development, which offers

great promise of unified prediction methods for wing-dominated flows, including the prediction of vortex breakdown.

Smith, J. M.

"DOES FAA NEED A NEW SYSTEM TO TRACK WAKE INCIDENTS?"

Government Computer News, October 1994, Vol. 13, No. 23, p. 16

An internal report from the Federal Aviation Administration (FAA) calls for a tracking system that will collect and analyze data on wake vortices so that air traffic controllers can give pilots better flight advice. The system should be able to allow air traffic controllers to determine airplane separation distances more accurately and foresee conditions that are likely to lead to wake vortex encounters. The proposal is prompted by recent air disasters that were traced to wake vortices. Vortex accidents occur when aircrafts are behind or below another. The FAA report is aware that there are no sufficient funds to develop such a system but suggests that instead of building a new one, the agency should just test a prototype vortex tracking system.

Smith, J. W., Mineck, R. E. and Neuhart, D. H.

"FLOW VISUALIZATION STUDIES OF BLOWING FROM THE TIP OF A SWEPT WING"

NASA TM-4217, November 1990, NASA Langley Research Center, Hampton, VA.

Flow visualization studies of blowing from the tip of a swept wing were conducted in the Langley 16-by 24-Inch Water Tunnel. Four wing tips, each with two independent blowing slots, were tested. The two slots were located one behind the other in the chordwise direction. The wing tips were designed to systematically vary the jet length, the jet in-plane exhaust direction (sweep), and the jet out-of-plane exhaust direction (anhedral). Each blowing slot was tested separately at two angles of attack and at four ratios of jet to free-stream velocity. Limited tests were conducted with blowing from both slots simultaneously. Blowing from the tip inhibited inboard spanwise flow on the upper wing surface near the tip. The jet path moved farther away from the tip as the ratio of jet velocity to free-stream velocity increased, and moved closer to the tip as angle of attack increased.

Smith, Jr., W. J. and King, C. J.

"EFFECT ON WING TIP VORTICES AND SONIC SHOCK ON ARMY AIRCRAFT IN FLIGHT"

Evaluation Report, January 1957, Beech Aircraft Corp., Wichita, KS

The report is a preliminary study of the oscillograph records obtained during the United States Army Aviation Board tests conducted in conjunction with the Air Force at Eglin AFB, Florida. In a limited number of flights involving QL-17, F-100, B-47, and L-19 aircraft, the following items were tentatively established: negative load factors higher than the minimum ultimate design requirements for normal category personal aircraft can reasonably be expected at higher cruise speed; every change in attitude

of the QL-17 resulting from vortex penetrations would have been more severe for a piloted Navion than for the QL-17 controlled by the autopilot; and separations greater than 30 seconds would be required by light aircraft following a B-47.

Smith, L. G., Maurice, M. S., Tyler, C., Seibert, G. L. and Miller, C. D.

"LASER VELOCIMETRY MEASUREMENTS OF VORTEX FLOWS ON A DELTA WING AT MACH 1.9"

WL-TR-93-3059, January 1993, Flight Dynamics Directorate, WPAFB, OH.

Off-body flow visualizations and fluid velocity measurements are conducted in a supersonic vortex flow. Three-dimensional laser velocimetry measurements are made in the leeward flowfield over a simple sharp-edged delta wing with 75-degree sweep angle. Tests are conducted at Mach 1.9 and Reynolds number of 2,400,000 based on model root chord. Measurements are made at 40 percent and 80 percent chord positions for 20- and 30-degree angles of attack and at 40 percent chord for 35 degrees. Mean velocities and turbulence intensities are measured on the five planes. Measurement accuracy is discussed in detail. The measurements define the location of the vortex core and provide the flowfield velocities surrounding the vortex. The difficulties inherent with seeding high velocity vortex flows are discussed.

Smith, M. J., Komerath, N., Ames, R., Wong, O. and Pearson, J.

"PERFORMANCE ANALYSIS OF A WING WITH MULTIPLE WINGLETS"

AIAA Paper 2001-2407, June 2001, Anaheim, CA.

This effort examined the potential of multi-winglets for the reduction of induced drag without increasing the span of aircraft wings. Wind tunnel models were constructed using a NACA 0012 airfoil section for the untwisted, rectangular wing and flat plates for the winglets. Testing of the configurations occurred over a range of Reynolds numbers from 161,000 to 300,000. Wind tunnel balances provided lift and drag measurements, and laser flow visualization obtained wingtip vortex information. The Cobalt60 unstructured solver generated flow simulations of the experimental configuration via solution of the Euler equations of motion. The results show that certain multi-winglet configurations reduced the wing induced drag and improved L/D by 15-30 percent compared with the baseline 0012 wing. A substantial increase in lift curve slope occurs with dihedral spread of winglets set at zero incidence relative to the wing. Dihedral spread also distributes the tip vortex. These observations supplemented previous results on drag reduction due to lift reorientation with twisted winglets set at negative incidence.

Smith, N. F.

"NUMERICAL EVALUATION OF MASS-FLOW COEFFICIENT AND ASSOCIATED PARAMETERS FROM WAKE-SURVEY EQUATIONS"

NACA TN-1381, August 1947, Langley Aeronautical Lab., Langley Field, VA

A method is presented for the determination by use of charts of mass-flow coefficient and associated flow parameters from pressure surveys in internal-flow systems. For isoenergetic flows the point mass-flow coefficient is shown to be an explicit function of the free-stream Mach number and of the static-pressure and total-pressure-loss coefficients at the measurement station. These parameters are easily determined from the test data; hence, their use provides a convenient method of evaluation of the point mass-flow coefficient. The charts presented cover a wide range of these parameters through the complete range of subsonic Mach numbers. The equations have also been evaluated for flows wherein mechanical or thermal energy is added, such as flows behind radiators or propellers. The fundamental principles may be applied to the measurement of flow from jet-propulsion units; however, under these conditions the mass of the fuel and the change in the value of the ratio of specific heats must be considered.

Smith, R.

"AN INVESTIGATION OF SUPERSONIC SWIRLING JETS"

Aeronautical Journal, Vol. 24, August 1973, pp. 167-178.

A theoretical and experimental investigation has been made into the effect of swirl on a supersonic jet. In certain circumstances a core of reversed flow can occur along the axis of symmetry and the jet mixes much more quickly with the ambient air than does the corresponding non-rotating jet. A characteristic calculation has been performed for the first cell in the case where the axial flow is not reversed. This indicates a shortening of the cell length and the formation of shocks nearer the nozzle.

Smith, R.

"HYPERSONIC SWIRLING FLOW PAST BLUNT BODIES"

Aeronautical Quarterly, Vol. 24, 1973, pp. 241-251.

The effect of swirl on the high-speed flow past blunt bodies is analyzed by assuming constant density in the region between the shock wave and the body. For small swirl the stand-off distance is only slightly affected, but it is shown that there is a critical value of the swirl parameter which, if exceeded, will cause a jump in the position of the shock. This is demonstrated by solving the full constant-density equations for the flow past a sphere and by a perturbation expansion in powers of the density ratio across the shock for a more general body shape. The perturbation solution shows that the pressure coefficient on the body is constant at the critical swirl number.

Smith, R. K.

"ACCURATE DETERMINATION OF A BALANCED AXISYMMETRIC VORTEX IN A COMPRESSIBLE ATMOSPHERE"

Tellus, Vol. 58A, 2006, pp. 98-103.

We give a simple method to calculate without approximation the balanced density field of an axisymmetric vortex in a compressible atmosphere in various coordinate systems given the tangential wind speed as a function of radius and height and the vertical density profile at large radius. The method is generally applicable, but the example considered is relevant to tropical cyclones. The exact solution is used to investigate the accuracy of making the anelastic approximation in a tropical cyclone, i.e. the neglect of the radial variation of density when calculating the gradient wind. We show that the core of a baroclinic vortex with tangential wind speed decreasing with height is positively buoyant in terms of density differences compared at constant height, but at some levels may be interpreted as cold-cored or warm-cored depending on the surfaces along which the temperature deviation is measured. However, it is everywhere warm-cored if the potential temperature deviation is considered. In contrast, a barotropic vortex in a stably-stratified atmosphere is cold-cored at all levels when viewed in terms of the temperature deviation at constant height or constant vertical component, but warm-cored when viewed in terms of the potential temperature deviation along these surfaces. The calculations provide a possible explanation for the observed reduction in surface air temperature in the inner core of tropical cyclones.

Smith, S. C. and Kroo, I. M.

"COMPUTATION OF INDUCED DRAG FOR ELLIPTICAL AND CRESCENT-SHAPED WINGS"

J. Aircraft, Vol. 30, No. 4, July-August 1993, pp. 446-452

Recent interest in the induced drag characteristics of crescent-shaped wings has led to a closer look at the methods used for determination of induced drag from computational aerodynamic methods. Induced drag may be computed by integration of surface pressure or by evaluation of a contour integral in the Trefftz plane. A high-order panel method was used to study the induced drag of elliptical and crescent-shaped wings using both techniques. Induced drag computations using surface pressure integration were strongly affected by panel density and angle of attack. Drag computations for the crescent wing were especially sensitive to spanwise panel density because of the complex flowfield near the tip. Trefftz-plane results for the two wing planforms were not sensitive to panel density or angle of attack. The effect of correctly modeling the force-free, rolled-up wake geometry on the predicted span efficiency was demonstrated for both wing planforms. The span efficiency predicted from Trefftz-plane integration was about 0.97 for the elliptical wing and 0.99 for the crescent wing, both somewhat less than the classical theoretical maximum for planar wings. Most of the apparent drag reduction of the crescent wing claimed in previous studies was probably an artifact of the surface-pressure integration. The slightly higher span efficiency for the crescent wing was attributed to a more nearly elliptical spanwise lift distribution.

Smith, S. C. and Kroo, I. M.

"INDUCED DRAG COMPUTATIONS ON WINGS WITH ACCURATELY MODELED WAKES"

A technique has been developed for numerically computing the force-free wake shape downstream of finite wings, based on the need for very accurate integration of induced drag in the Trefftz-plane. An $AR = 7$ elliptical wing with straight trailing edge was used to study the influence of the computed wake shape on induced drag. A traditional vortex-lattice relaxation method produced a wake that led to a 9% error in Trefftz-plane drag. The new method presented here obtains more accurate wing-induced velocities from a high-order panel method, while relying on the well-behaved nature of the discrete-vortex wake model for the wake-induced velocities. The induced drag with the wake produced by this hybrid scheme agreed with the drag predicted with a straight wake within 0.1%, consistent with high-resolution pressure integration. These and other cited results indicate that the hybrid scheme produces wakes of sufficient accuracy to enable Trefftz-plane integration of drag on the force-free wake.

Smith, S. T.

"MODELING OF WAKE-VORTEX AIRCRAFT ENCOUNTERS"

MS Thesis, April 1999, Howard University, Washington, DC

There are more people passing through the world's airports today than at any other time in history. With this increase in civil transport, airports are becoming capacity limited. To increase capacity and thus meet the demands of the flying public, the number of runways and number of flights per runway must be increased. In response to the demand, the National Aeronautics and Space Administration (NASA), in conjunction with the Federal Aviation Administration (FAA), airport operators, and the airline industry are taking steps to increase airport capacity without jeopardizing safety. Increasing the production per runway increases the likelihood that an aircraft will encounter the trailing wake vortex of another aircraft. The hazard of a wake vortex encounter is that heavy load aircraft can produce high intensity wake turbulence, through the development of its wing-tip vortices. A smaller aircraft following in the wake of the heavy load aircraft will experience redistribution of its aerodynamic load. This creates a safety hazard for the smaller aircraft. Understanding this load redistribution is of great importance, particularly during landing and take-off. In this research wake vortex effects on an encountering 10% scale model of the B737-100 aircraft are modeled using both strip theory and vortex lattice modeling methods. The models are then compared to data taken in the 30 ft x 60 ft wind tunnel at NASA Langley Research Center (LaRC). The accuracy of the models for a reduced geometry, such with the horizontal stabilizer and the vertical tail removed, is also investigated. Using a 10% error in the circulation strength and comparing the model's results with the experiment illustrates the sensitivity of the models to the vortex circulation strength. It was determined that both strip theory and the vortex lattice method give accurate results when all the geometrical information is used. When the horizontal stabilizer and vertical tail were removed there were difficulties modeling the side force coefficient and pitching moment. With the removal of only the vertical tail unacceptable errors occurred when modeling the side force coefficient and yawing moment. Lift could not be accurately modeled with either the full geometry or the reduced geometry.

Smith, S. T.

"INVESTIGATION OF WAKE VORTEX AIRCRAFT ENCOUNTERS; FINAL REPORT"

USGRDR0122, March 1999, Howard University, Washington, DC

The National Aeronautics and Space Administration is addressing airport capacity enhancements during instrument meteorological conditions through the Terminal Area Productivity (TAP) program. The major goal of the TAP program is to develop the technology that will allow air traffic levels during instrument meteorological condition to approach those achieved during visual operations. The Reduced Spacing Operations (RSO) subelement of TAP at the NASA Langley Research Center (LaRC) will develop the Aircraft Vortex Spacing System (AVOSS). The purpose of the AVOSS is to integrate current and predicted weather conditions, wake vortex transport and decay knowledge, wake vortex sensor data, and operational definitions of acceptable strengths for vortex encounters to produce dynamic wake vortex separation criteria. The proposed research is in support of the wake vortex hazard definition component of the LaRC AVOSS development research. The research program described in the next section provided an analysis of the static test data and uses this data to evaluate the accuracy vortex/wake-encounter models. The accuracy of these models has not before been evaluated using experimental data. The research results also presented the first analysis of the forces and moments imparted on an airplane during a wake vortex encounter using actual flight test data.

Smith, T. B. and MacCready, Jr., P. B.

"AIRCRAFT WAKES AND DIFFUSION ENHANCEMENT"

MRI63-FR-71, May 1963, Meteorology Research Inc., Altadena, CA

Studies have been made of the effect of an aircraft wake on the size and growth characteristics of a cloud of material disseminated from the aircraft. Smoke released from a Cessna 180 has been measured on several occasions to determine the dimensions of the wake at various distances behind the aircraft. Results indicate that the wake descends for a short time at a rate which approximates the calculated downwash velocity but soon slows appreciably to a much smaller descent rate. This effect limits the usefulness of the aircraft wake in downward propagation of material under light turbulence conditions.

Smith, W. G. and Lazzeroni, F. A.

"EXPERIMENTAL AND THEORETICAL STUDY OF A RECTANGULAR WING IN A VORTICAL WAKE AT LOW SPEED"

NASA TN-339, October 1960, NASA Ames Research Center, Moffett Field, CA

A systematic study has been made, experimentally and theoretically, of the effects of a vortical wake on the aerodynamic characteristics of a rectangular wing at subsonic speed. The vortex-induced lift was calculated by several theoretical methods including strip theory, reverse-flow theory, and reverse-

flow theory including a finite vortex core. In addition, the Prandtl-lifting-line theory and the Weissinger theory were used to calculate the spanwise distribution of vortex-induced loads.

Smits, A. J. and Kummer, R. P.

"THE INTERACTION AND MERGING OF TWO TURBULENT LINE VORTICES"

AIAA Paper No. 1985-0046, Reno, NV, January 1985

An experimental investigation of the interaction and merging of two turbulent line vortices is described. The vortices were generated by two airfoils set at opposite angles of attack, and they were of opposite sign and equal strength. As the vortices proceed downstream, they rotate around each other, and eventually they merge to produce a dominant, central vortex, with vestigial traces of the original vortices. Mean flow and turbulence measurements were made throughout the merging zone. The circulation profiles varied logarithmically with radius, for a considerable radial extent, at all stations. The turbulent shear stresses appeared to be simply related to the mean velocity gradients, and it seems that first-order turbulence models may be adequate to describe the merging process.

Snedeker, R. S.

"EFFECT OF AIR INJECTION ON THE TORQUE PRODUCED BY A TRAILING VORTEX"

J. Aircraft, Vol. 9, No. 9, September 1972, pp. 682-684

An experiment was performed to determine the effect of air injection on the torque produced by a trailing vortex. The results of this experiment was limited to measurement at a single axial station. It was shown that the torque induced by the vortex on a typical wing changes very little in the near field.

Snedeker, R. S.

"A COMPARISON OF THE TRAILING VORTEX MEASUREMENTS OF POPPLETON WITH INVARIANT MODELING COMPUTATIONS"

ARAP Tech. Memo 72-5, November 1972, Aeronautical Research Assoc. of Princeton, Princeton, NJ

The trailing vortex measurements made in a wind tunnel by Poppleton were used as a basis for comparison with computations made by application of the invariant modeling method. The measured profiles of mean and turbulent velocity at a point downstream of the vortex generator were used as initial conditions for the computation. A comparison was then made between the measured and computed profiles at a point further downstream. The comparison revealed that the computation, which was based on a two-dimensional form of the theory, gave poor agreement with the measured data, except in the case of the mean tangential velocity. It was concluded that the lack of agreement was primarily a result of the strong axial or three-dimensional effects which were evident throughout most of the range of the measurements. It was suggested that a form of the theory in which axial

effects are included, and which is now under development at A.R.A.P., would be more appropriate for application to flows of the type studied by Poppleton.

Snedeker, R. S. and Bilanin, A. J.

"ANALYSIS OF THE VORTEX WAKES OF THE BOEING 727, LOCKHEED L1011, MCDONNELL DOUGLAS DC-10, AND BOEING 747 AIRCRAFT"

ARAP Report 245, July 1975, Aeronautical Research Assoc. of Princeton, Princeton, N.

A study has been made of the vortex wakes behind B-727, L1011, DC-10, and B-747 aircraft in several flight conditions. An analytical method is developed for the computation of the wake vortex patterns and their velocity profiles for these aircraft. The method, which is based on an extension of the Betz method for an inviscid wake, is further modified to include the effects of distributed wing drag and the computation of axial velocity profiles. Comparisons are made between wake vortex swirl velocity profiles computed for these aircraft and corresponding measurements made by the FAA in full-scale flyby tests. The results indicate that the inviscid calculation works well for simple wakes containing one predominant pair of vortices, such as those shed with the aircraft in its cruise or holding configuration. With flaps deployed for takeoff or landing, these aircraft, because of the segmented design of their flaps, produce complex wakes, which may contain as many as five pairs of vortices. It is concluded that the effects of drag on the inviscid structure of the vortices are small.

Snel, H. and van Holten, Th.

"REVIEW OF RECENT AERODYNAMIC RESEARCH ON WIND TURBINES WITH RELEVANCE TO ROTORCRAFT; DATA (AND RIDDLES) ON DYNAMIC INFLOW, FLOW FIELD OF YAWED ROTORS, AND ROTATING 3-D STALL"

Aerodynamics and Aeroacoustics of Rotorcraft, AGARD-CP-552, August 1995, pp. 7-1 to 7-11.

A review is given of recent research on the aerodynamics of wind turbine rotors. The following subjects are covered in extenso: The induced velocity field of rotors, including dynamic inflow and yawed flow effects. Stall delay on rotating blades, a new boundary layer formulation is outlined applicable to this phenomenon. Without any further discussion, also some references have been given concerning recent wind turbine research on: simulation methods of atmospheric turbulence, dynamic stall effects and comparisons between theory and experiments, and effect of several types of blade tips on radiated noise.

Snow, W. L., Burner, A. W. and Goad, W. K.

"PHOTOGRAMMETRIC TECHNIQUE USING ENTRAINED BALLOONS FOR IN-FLIGHT RANGING OF TRAILING VORTICES"

NASA TM-4129, October 1989, NASA Langley Research Center, Hampton, VA

A novel method for experimentally determining the radial distance of a probe aircraft from a trailing vortex is described. The method relies on photogrammetric triangulation of targets entrained in the vortex core. The report describes the theory and preliminary testing using laboratory mock-ups.

Snyder, D. and Memory, C.

"A MODIFIED VORTEX ALGORITHM FOR LOW REYNOLDS NUMBER, LOW ASPECT-RATIO WINGS"

AIAA Paper 2005-4608, June 2005, Toronto, Canada.

A numerical algorithm based on Prandtl's lifting line theory is developed and applied to low Reynolds number aerodynamic force prediction for wings with low aspect ratio. The algorithm accounts for Reynolds number through viscous effects on the two-dimensional section lift and drag forces. Improved low aspect-ratio behavior is achieved by allowing the trailing vortex sheet to roll up with the wing tip vortices. The results of the algorithm are compared with experimental measurements.

Snyder, Jr., M. H.

"EFFECTS OF A WINGTIP-MOUNTED PROPELLER ON WING LIFT, INDUCED DRAG, AND SHED VORTEX PATTERN"

Ph.D. Thesis, May 1967, Oklahoma State University, Stillwater, OK

Experimental investigations of the use of end-plates to control and to vary the wing lift distribution and induced drag are reviewed. An experimental investigation of a reflection-plane wing with a nacelle and propeller mounted at the wingtip is reported. Use of a rotor turning in the direction opposite to that of the wing's trailing vortex shifts the core of the trailing vortex outboard and downward. Use of a pro-vortex rotating rotor moves the core inboard. A counter-vortex turning propeller decreased drag; a vortex-turning propeller increases drag.

Snyder, T. and Povitsky, A.

"FAR-FIELD INDUCED DRAG PREDICTION USING VORTICITY CONFINEMENT TECHNIQUE"

Journal of Aircraft, Vol. 51, No. 6, November-December 2014, pp. 1953-1958.

The goal of this study is to show the efficiency of the wake-integral technique coupled with vorticity confinement method for the prediction of induced drag by inviscid numerical modeling. While the vorticity confinement method has previously been used to capture trailing vortices, its quantitative effect on improving wake-integral drag prediction has not been investigated. In the present study, parameters of vorticity confinement are tuned and the advantages of using a variable confinement parameter are demonstrated. A combination of vorticity confinement with the wake-integral technique indicates that the computational fluid dynamics-predicted induced drag for wing with and without winglet becomes insensitive to wake-integration plane location, the computed drag approaches its theoretical lifting-line value, and the spurious drag is suppressed.

So, J., Ryan, K. and Sheard, G. J.

"SHORT-WAVE INSTABILITIES ON A VORTEX PAIR OF UNEQUAL STRENGTH CIRCULATION RATIO"

Seventh International Conference on CFD in the Minerals and Process Industries, CSIRO, December 2009, Melbourne, Australia.

The creation of vortex pairs occurs in a range of industries, including mixing, transport, and plastic molding. In particular, vortex pairs are observed in the wake of aircraft, and are the cause of a significant hazard in the aviation industry. Instabilities, which grow on vortex pairs, have been shown to lead to rapid diffusion, thus limiting this safety concern. To date research has only considered instabilities growing on a vortex pair where each vortex has the same magnitude of circulation. However, in practice it is unusual to have an equal strength vortex pair. This investigation is the first to consider the instability modes that may develop on a Lamb-Oseen vortex pair of arbitrary circulation ratio. We find a significant change in the growth rates of all instability modes reported previously for an equal strength vortex pair. All simulations employ an accurate spectral-element method to discretize the domain coupled with a three-step time splitting scheme. A wide range of instability wavelengths is considered to ensure that all instability modes are captured. By identifying and enhancing the leading instability modes, we can enhance the dissipation of the vortex pair.

So, J., Ryan, K. and Sheard, G. J.

"LINEAR STABILITY ANALYSIS OF A COUNTER ROTATING VORTEX PAIR OF UNEQUAL STRENGTH"

Australian and New Zealand Industrial and Applied Mathematics Journal, Vol. 50, October 2008, pp. C137-C151.

An elliptic type instability of a counter rotating vortex pair of unequal strength was numerically investigated with a linear stability analysis method. The peak growth rates of the unstable modes were predicted. The instability characteristics were found to differ from an equal strength vortex pair, of either co-rotating or counter rotating vortices. This investigation serves as a fundamental model to the flow of two unequal strength vortices, which can be generated from the ends of aerodynamic surfaces of an aircraft, such as wing tips and ailerons. These results provide predictions of the vortex arrangements likely to develop three dimensional instabilities, which is known to promote the dissipation of the underlying vortex structure.

Sohn, M. H. and Chang, J. W.

"VISUALIZATION AND PIV STUDY OF WING-TIP VORTICES FOR THREE DIFFERENT TIP CONFIGURATIONS"

Aerospace Science and Technology, April 2011, pp. 1-7.

The planform, profile, and cross-sectional views of the wing-tip region of a half-wing model with an aspect ratio of 3.2 and three different wing configurations, namely, square-cut, simple fairing, and

Whitcomb's full winglet wing-tip, were visualized at various angles of attack using smoke-wire visualization technique. Visualization pictures clearly show that the wing-tip vortices at different angles of attack and wing-tip configurations had distinct formation and structure characteristics. A comparison of simple fairing and Whitcomb's winglet configurations shows that the wing-tip vortices of the Whitcomb's winglet configuration were reduced in strength and displaced outboard and upward, at least in the near-wake region. This resulted in an increased lift-to-drag ratio for the Whitcomb's winglet configuration. The changes in the wing-tip vortex characteristics and the improved aerodynamic performance of the winglet were confirmed by Particle Image Velocimetry measurements of the cross-flow velocity of the wing-tip trailing regions and the force measurement of the model.

Sohn, M. H. and Chung, H. S.

"EFFECTS OF STRAKE PLANFORM CHANGE ON VORTEX FLOW OF A DOUBLE-DELTA WING"

Journal of Aircraft, Vol. 44, No. 6, November-December 2007, pp. 1842-1848.

This study examines the effects of a strake planform change on the vortex characteristics of double-delta wings through wing-surface pressure measurements and the off-surface flow visualization of the wing-leeward flow region. Three different shapes of strakes (65/90 deg sweep cropped-delta, 79 deg sweep single-delta, and 72/84 deg sweep cropped-delta) were tested. The double-delta wing configuration with the 79 deg sweep single-delta shape strake produced a more concentrated vortex system at upstream locations and showed advanced coiling and downward movement of the strake and wing vortices compared with the other two configurations. However, the concentrated vortex system for the double-delta wing configuration with the 79 deg sweep single-delta shape strake tended to diffuse and break down much faster than the other two configurations as the flow proceeded downstream. The test results reveal that strake modification can greatly alter flow pattern around a double-delta wing.

Sohn, M. H., Lee, K. Y. and Chang, J. W.

"VORTEX FLOW VISUALIZATION OF A YAWED DELTA WING WITH LEADING-EDGE EXTENSION"

Journal of Aircraft, Vol. 41, No. 2, March-April 2004, pp. 231-237.

The development and interaction of vortices over a yawed delta wing with leading-edge extension (LEX) was investigated through off-surface flow visualization using micro water droplets and a laser beam sheet. Angles of attack of 12, 16, 20 and 24 deg were tested at sideslip angles of 0, -5 and -10 deg. The flow Reynolds number based on the main-wing chord was 182,000. The wing vortex and the LEX vortex coiled around each other while maintaining comparable strength and identity at a zero sideslip. The increase of angle of attack intensified the coiling and shifted the cores of the wing and LEX vortices inboard and upward. By sideslip, the coiling, the merging and the diffusion of the wing and LEX vortices increased on the windward side, whereas they became delayed significantly on the leeward side. Also, the migration behavior of vortices on the windward and leeward sides of the wing changed considerably. The present study confirms that the sideslip angle has a profound effect on the vortex

structure and interaction of a delta wing with LEX, which characterized the vortex-induced aerodynamic load.

Sohn, S.-I. and Hwang, W.

"NUMERICAL SIMULATIONS OF VORTEX SHEET EVOLUTION IN STRATIFIED SHEAR FLOW"

J. Physical Society of Japan, Vol. 74, 2005, pp. 1472-1478.

The nonlinear evolution of an interface subject to a parallel shear flow is studied based on the vortex sheet model. We perform numerical simulations of the vortex sheet in density stratified fluids by using the point vortex method. The numerical algorithm based on two types of regularization method improves the stability of the vortex method and provides solutions with much higher resolutions than previous results. The numerical results show that, for a smaller density ratio, the interface has a larger growth rate and a more singular vortex sheet strength and curvature at late times. It is also found that, for an infinite density ratio, the interface has a solution of a traveling wave with no deformations.

Sohn, Y. J., Park, B. H. and Han, Y. O.

"INTERACTION OF TIP VORTICES GENERATED BY TWO BLADED ROTOR COMPOSED OF DIFFERENT PITCH ANGLES IN A HOVER"

AIAA Paper No. 2011-0678, January 2011, Orlando, FL.

Interaction between tip vortices generated by two bladed rotors with slightly different pitch angles was investigated with the use of laser Doppler velocimetry. The velocity field was measured at 20 different wake ages within one revolution of rotor blade. The swirl velocity of the tip vortex generated by the first blade was found to have a self-similar behavior while that of the second blade was distorted in radial direction by the effect of vortex trail induced by the first blade. The axial velocity components of both tip vortices showed the merging process of both vortex filaments near the 236 degrees of wake age. The vortex core was substantially reduced in merging region making the vortex strength increase temporarily. Core growth, empirical model correlation for both swirl and axial velocity components were observed, and stretched filament of tip vortices was also found.

Solch, I., Holzaepfel, F., Abdelmoula, F. and Vechtel, D.

"PERFORMANCE OF ONBOARD WAKE-VORTEX PREDICTION SYSTEMS EMPLOYING VARIOUS METEOROLOGICAL DATA SOURCES"

Journal of Aircraft, Vol. 53, No. 5, September-October 2016, pp. 1505-1516.

In this work the accuracy of wake-vortex prediction of DLR's wake encounter avoidance and advisory system (WEAA) is analyzed by means of data gathered from a flight test campaign in April 2014. The system is based on airborne data exchange between aircraft and allows pilots to avoid potentially dangerous wake-vortex encounters. As the vortex evolution is strongly controlled by atmospheric

parameters, the acquisition of meteorological data is crucial for WEAA. The accuracy of the wake-vortex prediction is investigated, employing first the current automatic dependent surveillance (ADS-B) standard, which is then extended by additional meteorological data transmitted via telemetry, or data from numerical weather predictions.

Sollenberger, R. L. and Hale, M.

"HUMAN-IN-THE-LOOP INVESTIGATION OF VARIABLE SEPARATION STANDARDS IN THE EN ROUTE AIR TRAFFIC CONTROL ENVIRONMENT"

Proceedings of the Human Factors and Ergonomics Society, 55th Annual Meeting, 2011, pp. 66-70.

Human factors researchers from the FAA William J. Hughes Technical Center conducted a human-in-the-loop simulation to investigate variable lateral separation standards in the enroute air traffic control environment. Twelve Certified Professional Controllers participated in the study. In addition to the typical 5-mile separation standard for the en route environment, we used reduced and increased separation requirements in the study. We simulated reduced separation requirements (i.e., 3 miles) using a Single Sensor Radar Site Adaptation as well as for aircraft with either Automatic Dependent Surveillance-Broadcast or Performance-Based Navigation equipment. We simulated increased separation (i.e., 10 miles) for Unmanned Aircraft Systems. In addition, we simulated variable wake turbulence separation requirements for Airbus 380s and Very Light Jets. We also developed a set of support tools to assist the controllers in using the variable separation procedures. We identified several human factors issues that may affect air traffic controllers when using variable separation standards in the en route environment.

Soltani, M. R., Ghorbanian, K. and Nazarinia, M.

"EXPERIMENTAL INVESTIGATION OF THE EFFECT OF VARIOUS WINGLET SHAPES ON THE TOTAL PRESSURE DISTRIBUTION BEHIND A WING"

ICAS 2004, Paper 2004-2.11.3, Aug.-Sept. 2004, Yokohama, Japan.

A series of low-speed wind tunnel tests to investigate the effect of different winglet shapes and orientations on the flowfield of a swept wing were conducted. Both surface pressure and wake data at various angles of attack, -10 to 15 degrees were measured. Further, the flowfield around the wing is visualized using tufts. Four types of winglet shapes, spiroid (forward and aft), blended and wing grid are used in this investigation. The wake profile behind the wing at various angles of attack with different winglets is measured, too. Furthermore, the effect of Turbulator strip on the wing upper surface is examined. Results are compared with conditions of no winglets. The results indicate that the presence of winglets change the flowfield over and around the wing significantly. The total pressure in the wake of the model varies drastically when the wing is equipped with winglets.

Son, C., Oh, S. and Yee, K.

"ICE ACCRETION ON HELICOPTER FUSELAGE CONSIDERING ROTOR-WAKE EFFECTS"

Journal of Aircraft, Vol. 54, No. 2, March-April 2017, pp. 500-518.

To accurately predict the ice shape on the fuselage under rotor-wake effects, discrete modeling of individual tip vortices is essential to determine the local aerodynamic interactions between the vortex and the fuselage. To this end, the actuator surface model is developed and applied to the present study. Then, water-droplet-trajectory prediction, thermal analysis, and ice growth module are seamlessly integrated. This study aims to perform detailed analysis of the rotor downwash effects on ice that accretes on a helicopter fuselage and to determine the variation with respect to the forward flight speed. As a result of comprehensive numerical computations, the following conclusions are reached. First, the rotor inflow transforms the droplet trajectories, the location of ice accretion and the amount of ice are changed. 16.5 percent less ice is accumulated on the overall fuselage in the rotor-fuselage interaction case compared to the isolated fuselage case. Second, a clear-cut distinction of the icing locations on the fuselage is observed with various advance ratios. In hovering conditions, massive ice is accumulated on the tail-boom and fuselage nose region, where the tip vortices collide with fuselage. Due to the large collision area with high speed of droplets, 15.2 and 9.1 percent more ice is accumulated in hovering case than that of forward flight case with the advance ratio 0.075 and 0.15, respectively. However, as the forward speed grows from 0.15 to 0.2, the total mass of ice exponentially increases. In case of the advance ratio 0.2, 36 percent more ice is accumulated than that of the hovering case.

Sonnenschein, C. M., DiMarzio, C. A. and Clippinger, D.

"DATA ANALYSIS STUDY AND PERFORMANCE EVALUATION OF THE SCANNING LASER DOPPLER SYSTEM"

Interim Report NAS-8-30795, December 1974, Raytheon Company, Sudbury, MA

This report describes the data analysis performed on the laser Doppler system data to evaluate system performance, develop vortex location algorithms, and obtain vortex transport data during testing at Marshall Space Flight Center and early operations at JFK International Airport.

Sonnenschein, C. M., DiMarzio, C. A., Clippinger, D. H. and Toomey, D. W.

"AVIATION SAFETY RESEARCH AND TECHNOLOGY/HAZARD AVOIDANCE AND ELIMINATION"

Interim Report NAS-8-30795, October 1975, Raytheon Company, Sudbury, MA

This report describes the data analysis performed on the data from the Scanning Laser Doppler System during tests at Marshall Space Flight Center and at JFK International Airport through May 1975. Vortex tracks and flow fields are considered with several hundred tracks analyzed to determine data quality and average parameters of vortex tracks from different aircraft in different wind conditions.

Sonnenschein, C. M., DiMarzio, C. A., Clippinger, D. H. and Toomey, D. W.

"AVIATION SAFETY RESEARCH AND TRANSPORTATION/HAZARD AVOIDANCE AND ELIMINATION"

ER 76-4220, August 1976, Raytheon Company, Sudbury, MA

Data collected by the Scanning Laser Doppler Velocimeter System (SLDVS) was analyzed to determine the feasibility of the SLDVS for monitoring aircraft wake vortices in an airport environment. Data were collected on atmospheric vortices and analyzed. Over 1600 landings were monitored at Kennedy International Airport and by the end of the test period 95 percent of the runs with large aircraft were producing usable results in real time. The transport was determined in real time and post analysis using algorithms which performed centroids on the highest amplitude in the thresholded spectrum. Making use of other parameters of the spectrum, vortex flow fields were studied along with the time histories of peak velocities and amplitudes. The post analysis of the data was accomplished with a CDC-6700 computer using several programs developed for LDV data analysis.

Sonnenschein, C. M., Jelalian, A. V., Keene, W. H. and Campbell, R. B.

"DEVELOPMENT STUDY OF A THREE DIMENSIONAL LASER DOPPLER SYSTEM FOR THE MEASUREMENT OF ATMOSPHERIC WIND VELOCITY AND AIRCRAFT TRAILING VORTICES"

NAS-8-26800, January 1972, Raytheon Company, Sudbury, MA

The results of studies to determine required system parameters for atmospheric wind measurements are presented. Several system configurations are considered. Simulation programs were used to determine that the designed system could meet the accuracy requirements for vortex flow field measurements.

Sonnenschein, C. M., Jelalian, A. V., Keene, W. H., Harris, C. E. and Miller, C. R.

"REMOTE DETECTION OF TRAILING VORTICES"

NAS-8-30512, February 1970, Raytheon Company, Sudbury, MA

This report summarizes the results of the first successful remote detection of vortices with a CO₂ laser system. Sample signal spectra of vortices were obtained and results were compared with visualizations of the vortex made possible by introducing smoke into the flow field.

Sorbjan, Z.

"SIMILARITY OF STABLY STRATIFIED GEOPHYSICAL FLOWS"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 21, 2016, Springer International Publishing Switzerland, pp. 425-440.

The article reviews the gradient-based similarity theory of shear-dominated, stably-stratified turbulent flows. The gradient-based similarity scales are classified as explicit or implicit. The explicit

scaling employs the length scale as a specified function of height. Within the implicit type, the mixing length is locally related to various moments of turbulence. The analytical form of the explicit similarity functions of the Richardson number Ri is obtained based on experimental data collected in the atmospheric surface layer. The implicit similarity functions can be derived by renormalization of the explicit-type expressions. Since the implicit scales and similarity functions are not directly dependent on height, they are expected to be universally valid in shear-driven, stably-stratified turbulent flows, in the atmospheric boundary layer and in the upper atmosphere.

Sorensen, J. A., Hunter, C. G. and Shen, M. M.

"REQUIREMENTS FOR INTEGRATED FLIGHT AND TRAFFIC MANAGEMENT DURING FINAL APPROACH"

IEEE Plans '92 - Position Location and Navigation Symposium, Monterey, CA, March 1992, pp. 248-255

It is pointed out that significant runway throughput is lost due to ineffective control of aircraft spacing during final approach. The solution is to integrate the terminal air traffic management (ATM) automation process with cockpit avionics via data link. Components of the ultimate integrated ATM-cockpit design might include (a) an ATM spacing algorithm that accounts for wake vortex and runway occupancy spacing constraints; (b) downlink of desired final approach speed profile; (c) uplink of desired spacing and threshold crossing times; (d) a heads-up traffic display to provide pilot spacing guidance; (e) a flight management system to drive the aircraft to meet timing requirements; and (f) an ATM display to allow close monitoring of the landing process. The research required to develop this integrated ATM-cockpit concept is presented.

Sorensen, J. N.

"INSTABILITY OF HELICAL TIP VORTICES IN ROTOR WAKES"

Journal of Fluid Mechanics, Vol. 682, 2011, pp. 1-4.

The conditions for the appearance of instabilities in systems of helical vortices constitute an intriguing problem that still remains partly unsolved. The experimental study of Felli, Camussi and Di Felice has shed new light on some of the basic mechanisms governing the instability mechanisms.

Sorensen, J. N., Naumov, I. V. and Okulov, V. L.

"MULTIPLE HELICAL MODES OF VORTEX BREAKDOWN"

Journal of Fluid Mechanics, Vol. 683, 2011, pp. 430-441.

Experimental observations of vortex breakdown in a rotating lid-driven cavity are presented. The results show that vortex breakdown for cavities with high aspect ratios is associated with the appearance of stable helical vortex multiplets. By using results from stability theory generalizing Kelvin's problem on vortex polygon stability, and systematically exploring the cavity flow, we succeeded

in identifying two new stable vortex breakdown states consisting of triple and quadruple helical multiplets.

Sorensen, T., Thogersen, M. L., Nielsen, P., Grotzner, A. and Chun, S.

"ADAPTING AND CALIBRATION OF EXISTING WAKE MODELS TO MEET THE CONDITIONS INSIDE OFFSHORE WIND FARMS"

Report 5899, February 2008, EMD International A/S, Aalborg, Denmark.

The project has as purpose to improve the existing PARK models for calculating the wake loss within wind farms with a special emphasis on large offshore wind farms. The existing models are based on wind farms consisting of few onshore turbines and while there is no work underway to produce better models, developers and planners must use the existing models. These existing models are suspected of being inadequate at handling large offshore wind farms, but as this project shows, an intelligent use of model parameters can reduce the error and uncertainty when using them. Sensitivity studies are made and the models are tested and demonstrated through three case examples.

Sorokin, A. M. and Vladimirova, N. A.

"ALGORITHMS FOR GENERATION OF THE GRIDS FOR SOLVING EULER EQUATIONS AND COMPUTING FLOW FIELDS ABOUT AIRCRAFT CONFIGURATIONS (WING+FUSELAGE+TAIL, WING+SLOTTED FLAP) UNDER UNIFORM AND VORTEX FREESTREAM CONDITIONS"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 66-7.

Reasonably simple and effective algorithms are developed for generating computational grids around such complex configurations as wing + fuselage + tail and wing + slotted high-lift device (flap) to study multi-core vortex structures and determining aircraft aerodynamic characteristics under uniform and disturbed vortical freestream conditions. Advantages and disadvantages are analyzed to evaluate various approaches to constructing surface and off-surface (3D - spatial) grids around complex geometry bodies: composite overlapping 'chimera'-type grids, multi-block and single-block structured grids, etc. A technology is proposed of 'fitting' the horizontal and vertical tails and wing high-lift slotted device into the grid topology around simpler configurations (wing, wing + fuselage). New gridding algorithms are combined with the code EULERCON that solves the 3-D Euler equations and modified solver versions are developed that incorporate additional aircraft surfaces (tail unit and flaps).

Sotiropoulos, F., Webster, D. R. and Lackey, T. C.

"EXPERIMENTS ON LAGRANGIAN TRANSPORT IN STEADY VORTEX-BREAKDOWN BUBBLES IN A CONFINED SWIRLING FLOW"

J. Fluid Mech., Vol. 466, 2002, pp. 215-248

In a recent study, Sotiropoulos et al. (2001) studied numerically the chaotic particle paths in the interior of stationary vortex-breakdown bubbles that form in a closed cylindrical container with a rotating lid. Here we report the first experimental verification of these numerical findings along with new insights into the dynamics of vortex-breakdown bubbles. We visualize the Lagrangian transport within the bubbles using planar laser-induced fluorescence (LIF) and show that even though the flow fields are steady - from the Eulerian standpoint - the spatial distribution of the dye tracer varies continuously, and in a seemingly random manner, over very long observation intervals. Sequences of instantaneous LIF images also show that the steady bubbles exchange fluid with the outer flow via random bursting events during which blobs of dye exit the bubble through the spiral-in saddle. The experimental Poincare maps are in good agreement with the numerical computations. We apply this method to visualize the dynamics in the interior of the vortex-breakdown bubble that forms in the wake of the first bubble for governing parameters in the steady, two-bubble regime. In striking contrast with the asymmetric image obtained for the first bubble, the time-averaged light intensity field for the second bubble is remarkably axisymmetric. Numerical computations confirm this finding and further reveal that the apparent axisymmetry of this bubble is because orbits in its interior exhibit quasi-periodic dynamics. We argue that this stark contrast in dynamics should be attributed to differences in the swirl-to-axial velocity ratio in the vicinity of each bubble. By studying the bifurcation of a simple dynamical system, with manifold topology resembling that of a vortex-breakdown bubble, we show that sufficiently high swirl intensities can stabilize the chaotic orbits, leading to quasi-periodic dynamics.

Soudakov, G. G.

"NONLINEAR ASYMPTOTIC MODEL OF THE FAR VORTEX WAKE BEHIND AN AIRCRAFT FLYING THROUGH THE TURBULENT AIR"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 162-175

The paper considers evolution of several endless vortex filaments having a specified internal structure with accounting for the ground proximity and air turbulence effects. The vortex filaments are divided into rectilinear segments and the velocities induced by them are calculated using the Biot-Savart formula. To evaluate a singularity appearing in determining the velocity at the point of the segment itself, asymptotic methods are used. The velocity at the point of a vortex filament is a sum of the velocities induced by vortex filaments and by a stochastic function that models the atmospheric turbulence. The atmospheric turbulence was modeled using the von Karman model. The problem on the evolution of vortex filaments was solved in the nonlinear formulation, that is, without an assumption that disturbance amplitudes are small as compared to the distance between the vortices. The vortex system lifetime was studied, depending on various parameters, as well as the physical effects associated with the presence of a multi-core structure. Both the case of symmetrical vortex filament motion and the general case are considered.

Soudakov, G. G.

"ENGINEERING MODEL OF THE WAKE BEHIND AN AIRCRAFT"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 95-110

This paper is devoted to the study of the aircraft vortex wake using an engineering approach based on similarity laws. The landing regime of an aircraft is considered where a multi-vortex wake system forms. Vortex parameters behind an aircraft are obtained both in the near field and in the far field with considering the circulation loss effect.

Soudakov, G. G. and Zamyatin, A. N.

"THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF EXTERNAL TURBULENCE EFFECT ON AIRCRAFT VORTEX WAKE"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

The problem under investigation was to obtain the real flight data about spatial kinematical and geometrical parameters of aircraft wake at various meteorological conditions. The flight conditions were close to the landing ones. Hot-wire measurements were made to obtain the flow fields of the mean velocity vector in the vortex area. Furthermore, as a result of measuring the mean velocity distribution in the vortex area the evaluation of the geometrical parameters of the vortex can be made. This information was supplemented by the geometrical parameter measurements using the visualization and stereophotogrammetric technique. In these investigations smoke visualization was used for the qualitative evaluation of the process of vortex forming and evolution and for measuring the geometrical vortex parameters as a function of time. CFD method of calculation of the near and far wake parameters is presented based on 2D RANS. A new non-linear two-scale eddy viscosity model is proposed which considers the presence of two greatly different turbulence scales (vortex turbulence scale is about 10 m, ambient atmosphere turbulence scale is about 200 m).

Soudakov, G. G., Voyevodin, A. V. and Zubtsov, A. V.

"ALLEVIATION OF THE VORTEX WAKE BEHIND AN AIRCRAFT"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 183-190

This work dwells upon the vortex wake behind a heavy aircraft. Vortex wake parameters characterizing the aircraft wake vortex hazards to an encountering aircraft are determined. Cases are considered where the most important among the parameters is the lifetime of the vortex wake. Using the model of a four-core vortex wake, it is shown that a redistribution of circulation over the wing could lead to a significant decrease in the wake lifetime. An assessment is made for a minimum possible landing value of the wake lifetime. Computation of flow about the B747-400 aircraft during landing has showed that variation of flap deviation angles could result in decreasing the vortex wake lifetime by a factor of 1.5 and 2 compared to a standard case.

Soukhomlinov, V. S., Sheverev, V. A. and Otugen, M. V.

"EVOLUTION OF A VORTEX IN GLOW DISCHARGE PLASMA"

Physics of Fluids, Vol. 17, May 2005, pp. 058102-1 to 058102-4

The evolution of a vortex in glow discharge plasma is studied analytically. Specifically, the mechanism of local energy deposition into the flow by the plasma is considered and its effect on the structure of an inviscid vortex is analyzed. The vortex is modeled by a set of Euler's equations while the energy transferred by the plasma into the gas is represented by Rayleigh mechanism. In this mechanism, the amount of heat addition is a function of local gas density. The analysis indicates that the plasma can have a considerable effect on the structure of a vortex. The inviscid calculations show that in a uniform discharge, a 1 cm vortex dies out in a fraction of a second.

Soule, H. A. and Miller, M. P.

"THE EXPERIMENTAL DETERMINATION OF THE MOMENTS OF INERTIA OF AIRPLANES"

NACA TR-467, January 1934, Langley Aeronautical Lab., Langley Field, VA

The application of the pendulum method to the experimental determination of the moments of inertia of airplanes is discussed in this report. Reference is made to the effects of the air, in which the airplane is immersed, on the swinging tests and to the procedure by which these effects are considered. This procedure has been used for some time, and the data on several airplanes for which the moments of inertia have been found are included.

Sousa, J. M. M. and Pereira, J. C. F.

"ROLLUP REGION OF A TURBULENT TRAILING VORTEX ISSUED FROM A BLADE WITH FLOW SEPARATION"

Experimental Thermal and Fluid Science, Vol. 20, 2000, pp. 150-161.

This paper presents the results of an experimental investigation on the near field of a tip vortex generated by a blade at moderate incidence. The experiments were conducted at $Re = 15000$ and the boundary layer over the blade separated around midchord on the upper surface. Laser-Doppler measurements of the turbulent flow ($Tu = 1.5$ percent) were performed at various stations downstream of the blade. The three components of the mean velocity field and turbulent attributes were quantified at cross-planes, characterizing both the blade wake and the tip vortex structure. This allowed the analysis of the rollup and initial stages of decay of the tip vortex in the light of known theories and models. The axial velocity defect at the center of the vortex core evolved as $(1/x)\log x$, without displaying any significant outgrowth imposed by the separated flow upstream. Momentum balances were also carried out at a station downstream to the conclusion of vortex rollup. The approximate axisymmetry of the flow field in the trailing vortex was used to formulate the balances in a cylindrical

coordinate system. Among other observations, it was seen that an adverse axial pressure gradient developed in the vortex core, which reinforced the tenacity of the axial velocity defect. In contrast, an area influenced by a favorable pressure gradient was found outside the core.

South, P.

"A SIMPLE THEORY OF VORTEX BURSTING"

Report LR-414, November 1964, National Research Laboratories, Ottawa, Canada.

This report proposes a simple model to explain the phenomenon of vortex bursting. The model considers the steady state axial pressure and momentum forces on an element of a vortex core in the presence of an external static pressure gradient, and the changes in core radius that must take place for this steady state to be maintained. A particular idealized vortex model is proposed, and it is shown that the vortex will grow infinitely rapidly when subjected to an external static pressure rise greater than a certain critical amount that depends on the initial core helix angle and axial dynamic pressure. Some experimental data are presented that show that the predictions are in fairly good agreement with the observed results.

Spahr, J. R.

"THEORETICAL PREDICTION OF THE EFFECTS OF VORTEX FLOWS ON THE LOADING, FORCES, AND MOMENTS OF SLENDER AIRCRAFT"

NASA TR R-101, 1961, NASA Ames Research Center, Moffett Field, C.

A general calculative method based on slender-body theory is developed for predicting the paths of vortices in the presence of wing-body combinations at subsonic, transonic, and supersonic speeds, and the influence of the vortices on the loading forces and moments acting on the combinations. The method is applied to wing-body combinations to study the effects of vortex strength and initial position, combined angles of pitch and roll and wing aspect ratio on the vortex paths and induced loads. The results indicate that these effects were significant because of the dependence of the vortex paths and induced loads on the vortex strengths and on the proximity of the vortices to the surface of a wing-body combination. Comparison of theoretical and experimental results indicated that the vortex paths and vortex-induced force and moments for slender-wing-body combinations were closely predicted by the slender-body method but for non-slender combinations these characteristics were only approximated. The application of an alternate method based on reverse flow theory improved the predictions of the vortex-induced forces and moments for the latter combinations but impaired those for slender combinations. The induced forces and moments on the non-slender combinations were sufficiently small that the total forces and moments could be predicted adequately through the use of either method.

Spahr, J. R. and Dickey, R. R.

"WIND-TUNNEL INVESTIGATION OF THE VORTEX WAKE AND DOWNWASH FIELD BEHIND TRIANGULAR WINGS AND WING-BODY COMBINATIONS AT SUPERSONIC SPEED"

NACA RM-A53D10, June 1953, Langley Aeronautical Lab., Langley Field, VA

The flow field behind triangular wings (aspect ratios of 0.67 to 4) alone and in combination with a pointed cylindrical body has been investigated at Mach numbers of 1.5 and 2.0 through an angle-of-attack range of 0 degrees to 24 degrees. The character of the vortex wake was observed by means of the vapor-screen flow-visualization technique, and certain regions of the downwash field associated with the observed vortex systems were surveyed. Estimates of the downwash distributions were also made using a method based on existing theories, and the results have been compared with experiment. The initial character and subsequent behavior of the wing trailing vortex wake with or without the body present were observed to vary significantly with the wing aspect ratio and with the angle of attack. For low-aspect-ratio wings at small angles of attack and for large-aspect-ratio wings throughout the test angle-of-attack range, the nature and behavior of the wake is in accord with theoretical predictions; that is, the vortex wake leaves the wing trailing edge as a sheet and proceeds to roll up into one or two (depending on the type of spanwise load distribution) regions of vorticity behind each wing panel as it progresses downstream.

Spaid, F. W. and Keener, E. R.

"BOUNDARY-LAYER AND WAKE MEASUREMENTS ON A SWEEPED, CIRCULATION-CONTROL WING"

J. Aircraft, Vol. 28, No. 11, November 1991, pp. 706-71.

Wind-tunnel measurements of boundary-layer and wake velocity profiles are presented for a swept, circulation-control wing. The model is a semispan, rectangular wing with a constant cross section mounted on the tunnel sidewall at a sweep angle of 45 deg. A circulation-control slot is located ahead of the trailing edge on the upper surface. Flow surveys were obtained at midsemispan at freestream Mach numbers of 0.425 and 0.70. Boundary-layer profiles measured on the forward portions of the wing are approximately streamwise and two dimensional. The flow in the vicinity of the jet exit and in the near wake is highly three dimensional. The jet flow near the slot on the Coanda surface is directed normal to the slot. Near-wake surveys show large outboard flows at the center of the wake. The variation in the lower-surface separation location with blowing rate was determined from boundary-layer measurements at Mach 0.425. In addition to providing an experimental description of a complex, three-dimensional flowfield, these data should serve as test cases for computational fluid dynamics methods.

Spalart, P. R.

"ON THE MOTION OF LAMINAR WING WAKES IN A STRATIFIED FLUID"

J. Fluid Mech., Vol. 327, November 1996, pp. 139-160

We present numerical solutions for 2D laminar symmetric vortex systems descending in a stably stratified fluid within the Boussinesq approximation. Three types of flow are considered: (I) tight vortices; (II) those deriving from an elliptical wing lift distribution; and (III) those deriving from a 'high-lift' distribution, with a part-span flap on the wing. The non-dimensional stratification ranges from zero to moderate, as it does for airliners. For types I and II, with high Reynolds numbers and weak stratification, the solutions confirm the theory of Scorer and Davenport (1970). Contrary to common conceptions and observations in small-scale experiments, the descent velocity increases exponentially with time, as the distance between vortices decreases and the circulation of the vortices proper is conserved. With moderate stratification, wakes with sufficient energy also attain the accelerating regime, until the vortices make contact. However, they first experience a rebound, which is both of practical importance and out of reach of simple formulas. We argue that airliner wakes have very little inherent diffusion, and that a rapid end to the wake's descent must reveal effects other than simple buoyancy. In particular, stratification promotes the Crow instability.

Spalart, P. R.

"WAKE-VORTEX PHYSICS: THE GREAT CONTROVERSIES"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 33-44

Several controversies are articulated, which are unresolved and seen to be serious obstacles to a consensus and to the use of scientific knowledge in wake-turbulence precautions and regulations. The questions are as follows. Do vortices decay? Why does ATC work today? Do wakes ever rise? What is the effect of stable atmospheric stratification? Are the vortices bathing in turbulence sustained by it (not atmospheric turbulence)? How much can happen to ONE vortex (destruction, cuts)? Better to use passive or active control strategy?

Spalart, P. R.

"AIRPLANE TRAILING VORTICES"

Annual Review of Fluid Mechanics, Vol. 30, Annual Reviews Inc., Palo Alto, CA, 1998, pp. 107-138

The formation, motion, and persistence of trailing vortices is surveyed, as relevant to the safety and productivity of air travel. Findings or shifts made since Widnall's 1975 Annual Review article are highlighted. Examined are the predictability of the vortices, particularly in terms of lifespan; the durability of multiple vortex pairs; the controversy between expectations of vortex decay and of vortex collapse; the many types of turbulence that may influence the flow; the rich interplay between the rotational and the axial velocity fields in the vortex; the various atmospheric and ground-related factors that dominate the late behavior; a few instances of wakes rising back; and the still unexplained bursting of the vortices. Prospects for detection and control are briefly covered.

Spalart, P. R.

"ON THE FAR WAKE AND INDUCED DRAG OF AIRCRAFT"

J. Fluid Mech., Vol. 603, 2008, pp. 413-430

A set of matched asymptotic expansions is proposed for the flow far behind an aircraft, with the primary purpose of identifying lift, thrust and drag, particularly induced drag, in a unified manner in integral statements of the momentum equation. The fluid in the far wake is inviscid and incompressible, and variations of total pressure are allowed, as are vortex sheets. A notable feature is that the Trefftz-plane approximation is not invoked; instead, the wake is taken as fully rolled-up, and the analysis proceeds without the assumption of light loading. Attention is paid to the absolute convergence of integrals over infinite domains and handling of discontinuities. The expansion includes a sink term, which appears new, so that the mass flux through a transverse plane is non-zero, as is the flux of mechanical energy. The lift can be formally attributed to the velocity induced by the bound vortex of the wing, which is at odds with some treatments, although consistent with Prandtl's analysis over a ground plane.

Spalart, P. R.

"HOW CAN WE TRULY REDUCE THE WAKE-VORTEX HAZARD BY MODIFYING THE WING?"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

The airframers wish to contribute to the combination of safety and airport capacity, in the context of wake turbulence. When viewing the airplane as the leader, the airframers are ready for limited compromises to make the wakes less troublesome. Characteristics that may be traded for this include: drag, lift, weight, complexity, control authority, pilot workload, or noise. The Airbus A380 is the first model for which such steps are, to our knowledge, being taken. Here we attempt to concretely identify what could make a less troublesome wake. A classic trade between wake properties involves the circulation and the effective span of a single vortex pair. Given the weight and speed, circulation times effective span is fixed. Lowering circulation makes a weaker wake, and encounters are less severe. However the wake descends more slowly, and its Crow instability grows more slowly; the wake lingers. Both effects increase the probability of an encounter. Thus, the preference between circulation and effective span depends on the policy (avoidance or tolerance of encounters) and on factors such as the leader and follower sizes, actual in-trail separation, phase of flight, and weather. The trade is not simple. Flow-control designs can be classified as active, when the configuration is varied cyclically to initiate an instability, or passive. Boeing's active system is discussed in this volume. The aim is wake collapse. Approaches such as tip turbines appear intermediate but are closer to passive systems, in that they divide and displace the vortices, and/or increase mixing. Most passive designs use a static geometry, winglets for example. The trade between circulation and effective span leaves little room. The known passive designs are presumed to produce 'weaker' wakes, for the same circulation and effective span, making encounters less violent. The aim is wake alleviation. Common measures of a

wake's threat include the peak vorticity, peak velocity, and kinetic energy. Useful changes to these will be very difficult to demonstrate.

Spalart, P. R. and Wray, A. A.

"INITIATION OF THE CROW INSTABILITY BY ATMOSPHERIC TURBULENCE"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 18-1 to 18-8

The interaction between vortex pairs and well-developed isotropic turbulence is studied by Direct Numerical Simulation. It is a model of the effect of natural environmental disturbances on airplane wakes. The nondimensional turbulence intensity is in the range (0.02, 0.5), typical of airplanes. The most-amplified wavelength of the Crow instability is placed within the inertial range of the turbulence, which is typical in the atmosphere and fits the theoretical setting of Tombach and Crow & Bate. The vorticity peaks in cross-flow planes are tracked to reveal the deformation of the vortices. In agreement with visual observations, the Crow instability dominates in weak turbulence, whereas chaotic deformations are seen in stronger turbulence. The average wavelength is about 27% shorter than the most amplified one. The beginning of destruction is identified with the first changes in the connectivity of the lines; identifying the end of destruction is more elusive. The wake lifespans overlap those from flight tests, laboratory tests, and the theory of Crow & Bate. However, in strong turbulence, theory and simulation both predict shorter average lifespans than the tests do. The scatter in lifespans is almost as large in simulations as in flight tests; thus, the intermittence of turbulence appears to explain the scatter even without any other differences in conditions. We conclude that the predictability of wake destruction by this mechanism is very poor.

Spalart, P. R., Strelets, M.-Kh., Travin, A. K. and Shur, M. L.

"MODELING THE INTERACTION OF A VORTEX PAIR WITH THE GROUND"

Fluid Dynamics, Vol. 36, No. 6, 2001, pp. 899-908

The results of a numerical investigation of the interaction between an aircraft vortex wake (vortex pair) and the ground during the takeoff and landing phases are presented. The calculations were performed within the framework of the time-dependent two-dimensional Reynolds-averaged Navier-Stokes equations using the Spalart-Shur turbulence model generalizing the turbulent viscosity transport model of Spalart and Allmaras to the case of the flows with curved streamlines and rotation. Similar calculations were carried out based on the original Spalart-Allmaras model and the k- ω model of Menter. Some new qualitative and quantitative data on the distinctive features of the phenomenon under consideration are obtained.

Spalart, P. R., Strelets, M.-Kh., Travin, A. K. and Shur, M. L.

"MODELING THE TURBULENT VORTEX WAKE BEHIND A HIGH-LIFT WING"

Fluid Dynamics, Vol. 36, No. 5, 2001, pp. 726-733

A mathematical model and the results of a numerical simulation of the multiple vortex structure behind the high-lift wing (with deflected flaps) of a civil aircraft model are presented. The calculations are performed within the framework of the simplified (with allowance for the specific features of the flow under consideration) three-dimensional Reynolds equations using three turbulence models. The results obtained are compared with the experimental data; a considerable influence of the streamline curvature, typical of vortex flows, not only on the turbulence parameters but also on the parameters of the average flow is demonstrated. As a result, only one of the turbulence models considered, namely, that taking the streamline curvature and rotation effects on the turbulence into account, ensures acceptable accuracy of the main wake characteristics.

Spall, R. E.

"TRANSITION FROM SPIRAL- TO BUBBLE-TYPE VORTEX BREAKDOWN"

Phys. Fluids, Vol. 8, No. 5, May 1996, pp. 1330-1332

Numerical calculations employing the fully three-dimensional, time-dependent Navier-Stokes equations have been utilized to compute a transition from spiral- to bubble-type vortex breakdown for an unconfined longitudinal vortex. The transition was initiated through a small increase in the magnitude of the free-stream axial velocity deceleration. The resulting bubble structure, which consisted of a single toroidal recirculation cell, ultimately grew unstable. Transition back to a stronger spiral breakdown followed. Results are in qualitative agreement with experimental observations.

Spall, R. E.

"NUMERICAL STUDY OF A WING-TIP VORTEX USING THE EULER EQUATIONS"

Journal of Aircraft, Vol. 38, No. 1, January-February 2001, pp. 22-27

The issue of excessive diffusion of wing-tip vortex calculations is addressed. In particular, a second-order accurate pressure-based finite volume algorithm was employed to solve the Euler equations for the flow over a NACA 0012 rectangular wing at an angle of attack of 5 deg. A computational mesh was constructed that allowed for very localized grid clustering about the wing tip and about the vortex centerline over arbitrary downstream distances. Comparisons with existing experimental data show that the vortex strength and core radius are well preserved at 10 chords downstream from the wing leading edge. It is concluded that by employing well-designed computational grids, second-order accurate numerical algorithms may present a viable alternative to higher-order schemes in the solution of the tip vortex problem.

Spall, R. E. and Gatski, T. B.

"TURBULENT VORTEX BREAKDOWN: A NUMERICAL STUDY"

IUTAM Symposium on Dynamics of Slender Vortices, Aachen, Germany, August 31-September 3, 1997

Three-dimensional and axisymmetric solutions to the Reynolds-averaged Navier-Stokes equations have been obtained for turbulent vortex breakdown within a slightly diverging tube. Inlet boundary conditions were derived from experimental data for the mean flow and turbulence kinetic energy provided by Sarpkaya (Private Communications). The performance of both two-equation and full differential Reynolds stress models is evaluated. The experimentally determined location of breakdown was well predicted by the differential Reynolds stress model. However, the two-equation models failed to predict the occurrence of breakdown. Failure of the two-equation models is attributed to their inability to accurately account for Reynolds stress anisotropies. Further comparisons between the experimental data of Sarpkaya and the Reynolds stress model results are presented and discussed.

Spall, R. E., Gatski, T. B. and Grosch, C. E.

"A CRITERION FOR VORTEX BREAKDOWN"

Phys. Fluids, Vol. 30, No. 11, November 1987, pp. 3434-3440

A criterion for the onset of vortex breakdown over a wide range of the Reynolds number is proposed. Based upon previous experimental, theoretical, and numerical studies, as well as a new numerical study, an appropriately defined local Rossby number is used to delineate the region where breakdown occurs. Comparisons are made with previously suggested criticality parameters and the unique features of the proposed Rossby number parameter are shown. Several previous theoretical studies concentrating on inviscid standing-wave analyses for trailing wing-tip vortices are reviewed and reinterpreted, along with the previous numerical and experimental studies, in terms of the Rossby number parameter. For the case of trailing wing-tip-type vortices, it is shown that previous numerical studies were performed at lower Reynolds numbers than the corresponding laboratory experiments. Utilizing a consistently defined Reynolds number, Rossby number-Reynolds number plots of these previous vortex breakdown studies, for both trailing wing-tip and leading-edge vortices, are obtained. A criticality condition is identified for both types of vortices.

Spangler, S. B., Dillenius, M. F. E., Schwind, R. G. and Nielsen, J. N.

"ASSESSMENT OF A WAKE VORTEX FLIGHT TEST"

NEAR-TR-48, July 1974, Nielsen Engineering and Research Inc., Mountain View, CA

A proposed flight test program to measure the characteristics of wake vortices behind a T-33 aircraft was investigated. Several facets of the flight tests were examined to define the parameters to be measured, the anticipated vortex characteristics, the mutual interference between the probe aircraft and the wake, the response of certain instruments to be used in obtaining measurements, the effect of condensation on the wake vortices, and methods of data reduction. Recommendations made as a result of the investigation are presented.

Sparaco, P.

"TEST FACILITIES INAUGURATED"

Aviation Week & Space Technology, Vol. 158, No. 3, January 2003, p. 53

A European technology program dubbed Aircraft Wing with Advanced Technology Operations (Awiator) is expected to significantly advance studies on airflow control, wake vortices and aeroelasticity. In an initiative set to support the European Commission's (EC) four-year program, Onera French aerospace research agency has completed an innovative free-flight laboratory. It will enable scientists to scrutinize flight characteristics of catapult-launched scale models of aircraft, visualized with the help of a smoke screen. Measurements will be recorded on 20 video cameras while turbulence, vertical and lateral wind gusts will be generated by sophisticated simulation systems. Such tests are scheduled to complement earlier studies on the Airbus A380 mega-transport's wake vortices and, if needed, could help aviation authorities determine revised horizontal separations between heavy transports during final approach.

Spearman, M. L.

"INNOVATIVE CONCEPT FOR A HEAVY-LOAD AIRCRAFT UTILIZING A TWO-DIMENSIONAL WING"

AIAA Paper No. 2007-4439, Miami, FL, June 2007.

Heavy-load aircraft of conventional wing-body-tail design have become very large. Excessive size of such aircraft may present problems in the manufacturing process. In addition, large wing spans may cause some difficulties in ground handling. Increasing lift loads on large span cantilever wings will also increase the strength of the wing tip vortex. The concept presented herein proposes a means for substantially increasing the lift load capability of an aircraft without increasing the overall length and span of the configuration. The concept has a rectangular wing with a relatively low span and a large chord to provide the area required for high lift. Large fuselages are attached at each wing tip to provide the volume required for high lift. The fuselages serve as endplates for the wing and should preclude tip flow so that two-dimensional flow might be established on the wing. Elimination of the wing tip flow should prevent the formation of a tip vortex and eliminate the tip vortex hazard to trailing aircraft. Exploratory wind tunnel tests of such an aircraft concept have been conducted. Lessons learned from these tests are discussed herein to determine the validity of the concept.

Speijker, L.

"DEVELOPMENT AND APPLICATION OF THE WAVIR SAFETY ASSESSMENT METHOD FOR CURRENT PRACTICE SINGLE RUNWAY APPROACHES"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

The current separation minima stem from the early 70's. Although they have 'proven to be sufficiently safe', the current safety level is unclear and there is a deficiency of tools to support new

developments in operational usage at busy airports. The S-Wake project has proposed a probabilistic model to assess safety, and to evaluate the relation between wake vortex induced risk and aircraft separation distances. This probabilistic approach supports two commonly accepted rationales for acceptance of a newly proposed ATM concept (or procedure) by involved interest groups by showing that the number of wake vortex induced risk events: does not exceed some pre-defined, and agreed upon, safety requirement; and does not increase with the introduction of a new ATM procedure. The WAVIR methodology and tool-set has been extended and applied, following modeling improvements of all its major three sub-models: flight path evolution model, wake vortex evolution model, and wake encounter model. A safety assessment of single runway approaches under different weather, wind and operational conditions was carried out. The results show that the impact of the investigated procedural aspects - as compared to the impact of weather and wind conditions - is relatively small. Reduction of separation distances requires a reduction of the risk near the runway threshold, by measures that reduce the probability and/or consequences of such encounters. The risk assessment results also show that - for single runway approaches - the largest runway capacity improvement might be achieved through exploiting weather conditions favorable for a rapid decay or destruction of the vortices, in particular when located close to the runway threshold. This conclusion is supported by wake encounter data analysis from different sources (including ETWIRL data and NTSB data).

Speijker, L. J. P.

"S-WAKE FINAL REPORT FOR WORK PACKAGE 4, PROBABILISTIC SAFETY ASSESSMENT"

NLR TP-2003-248, March 2003, National Aerospace Lab., Amsterdam, The Netherlands.

This document describes work undertaken in WP4 'Probabilistic Safety Assessment' of the project S-WAKE for the European Commission. The study comprises a quantitative safety assessment of wake vortex induced risk related to single runway approaches under current practice flight regulations. In view of the uncertainties and the difficulties in understanding the wake vortex phenomena, a probabilistic approach has been followed to evaluate the safety related to different separation distances between landing aircraft on a single runway. This probabilistic model is based on a stochastic framework that incorporates sub models for wake vortex evolution, wake encounter, and flight path evolution, and relates the severity of encounters to possible risk events (i.e. incidents/accidents).

Speijker, L. J. P., Blom, H. A. P. and Kos, J.

"ASSESSMENT OF WAKE-VORTEX SAFETY TO EVALUATE SEPARATION DISTANCES"

CEAS/AAAF Conf. On Research for Safety in Civil Aviation, Paris, October 1999 (also TP-99454, October 1999, National Aerospace Laboratory, Amsterdam, The Netherlands)

The steady increase in air traffic imposes a need for enhanced airport capacity, and the desire to safely reduce existing separation standards. An important limiting factor in establishing required separation standards is the risk imposed by wake vortices. A probabilistic model is developed for the determination of wake vortex induced accident risk. The modeling approach is integrated within a

stochastic framework. Four probabilistic sub models are being used: wake vortex evolution model, wake vortex interaction model, aircraft control capability model, and flight path evolution model. This probabilistic model can be used for an assessment of wake vortex safety related to different ATM concepts or procedures. A safety management framework, which describes how to judge the acceptability of the obtained safety assessment results, is developed.

Speijker, L. J. P., Kos, J., Blom, H. A. P. and van Baren, G. B.

"PROBABILISTIC WAKE VORTEX SAFETY ASSESSMENT TO EVALUATE SEPARATION DISTANCES FOR ATM OPERATIONS"

NLR-TP-2000-326, June 2000, National Aerospace Laboratory, and ICAS 2000, Harrogate, UK

The steady increase in air traffic imposes a need for enhanced airport capacity, and the desire to safely reduce existing separation minima. An important limiting factor in establishing required separation minima is wake vortex induced risk. A novel probabilistic methodology is under development for the assessment of wake vortex induced accident risk. The methodology is integrated within a stochastic framework. Three probabilistic sub models are being used: wake vortex evolution model, wake encounter model and flight path evolution model. This probabilistic methodology can be used for an assessment of wake vortex safety of different Air Traffic Management (ATM) concepts or procedures. It provides a tool to evaluate separation distances for the current practice, and for promising new ATM concepts which may enable a safe reduction of current separation minima. Numerical results can be fed back to ATM designers, who can use these results to redesign or improve their proposed ATM concept. The safety management approach to regulate and control wake vortex induced risk can, and should, be based on an assessment of accident risk probabilities, followed by a comparison with risk criteria. Some guidelines for the development of a risk criteria framework, to be agreed upon by involved interest groups, are given. This paper outlines the probabilistic methodology, and illustrates its initial application for the single runway approach under current flight regulations.

Speijker, L. J. P., Vidal, A., Barbaresco, F., Gerz, T., Barny, H. and Winckelmans, G.

"ATC-WAKE: INTEGRATED WAKE VORTEX SAFETY AND CAPACITY SYSTEM"

IST-2001-34729, National Aerospace Lab., Amsterdam, The Netherlands, December 2005

The project ATC-Wake aims to develop an integrated system for ATC (Air Traffic Control) that would allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports. A variety of existing subsystems has been integrated within the ATC-Wake Integrated Platform, which was used in a test bed environment role: to evaluate the interoperability of the ATC-Wake system with existing ATC systems currently used at various European airports; to assess the safety and capacity improvements that can be obtained by local installation of the ATC-Wake system at various European airports; to evaluate operational usability and acceptability of the ATC-Wake system; and to make a plan and to assess the costs for further implementation and exploitation of the ATC-Wake IP platform into the system that can be installed at European airports. The Final Report provides

an overview of all the activities performed, including conclusions and recommendations to continue the exploitation towards installation of the ATC-Wake system at European airports.

Speijker, L., van Baren, G., Sherry, L., Shortle, J. and Rico-Cust, F.

"ASSESSMENT OF WAKE VORTEX SEPARATION DISTANCES USING THE WAVIR TOOLSET"

AIAA-IEEE 23rd Digital Avionics Systems Conference, Vol. 1, October 2004, pp. 2.E.2-1-2.E.2-11

Increases to the capacity of the National Airspace System (NAS), and reduction of delayed and cancelled flights, can be achieved by increasing the landing and takeoff capacity of the runways at the nation's busiest hub airports. NASA and the FAA are evaluating the feasibility of increasing runway capacity through reduced wake vortex separation distances between aircraft in the arrival and departure flows. Traditionally three methods have been used to determine safe wake vortex separation distances: (i) flight test experiments, (ii) historic operational data, and (iii) analytical models. This paper describes the WAVIR toolset, developed by the National Aerospace Laboratory NLR (the Netherlands), for evaluation of wake vortex separation distances. WAVIR is an analytic tool that uses stochastic models for wake vortex generation, wake vortex encounter, aircraft separation, and pilot/aircraft response to an encounter of varying magnitudes. The WAVIR tool provides the ability to evaluate the feasibility of different separation distances between fleets of heterogeneous aircraft under different operational, weather and wind conditions. The approach is applied to evaluate the safety related to current practice single runway arrivals.

Spence, G. T., Allerton, D. J., Le Moigne, A. and Qin, N.

"REAL-TIME MODEL OF WAKE VORTICES BASED ON LARGE EDDY SIMULATION DATASETS"

AIAA Paper No. 2005-6205, San Francisco, CA, August 2005.

An alternative model is presented to represent a counter rotating vortex pair for wake vortex interaction in a real-time flight simulation. Rather than describing the characteristics of the wake vortex system as an analytical model, this model is based upon directly accessing a three-dimensional time-varying dataset that is pre-computed by Large Eddy Simulations (LES). The model is designed to run on a low-cost PC and is integrated with a six-degree-of freedom real-time flight simulator. The success of using LES data as the basis of a wake vortex encounter model, depends on the ability to access the dataset in real-time. This paper focuses on implementation issues of the real-time data management aspects, and describes the data compression scheme implemented to reduce the size of the time-varying dataset. Preliminary comparisons of the model with traditional analytical wake vortex models are discussed together with discussion of flight-test data from several example interactions with wake vortices in a flight simulation.

Spence, G. T., Le Moigne, A., Allerton, D. J. and Qin, N.

"WAKE VORTEX MODEL FOR REAL-TIME FLIGHT SIMULATION BASED ON LARGE EDDY SIMULATION"

Journal of Aircraft, Vol. 44, No. 2, March-April 2007, pp. 467-475

An alternative approach is presented to represent a counter-rotating vortex pair for wake vortex interaction in a real-time flight simulation. Rather than using an analytical model, the model directly accesses a precomputed three-dimensional time-varying dataset. This dataset is generated using implicit large eddy simulations on unstructured grids. The methodology enables a realistic vortex decay to be reproduced with the apparition of short- and long-wave instabilities. The vortex model based on these simulations is designed to run on a personal computer and is integrated with a six-degree-of-freedom real-time flight simulator. The paper combines the use of large eddy simulation data as the basis of a wake vortex encounter model with methods to access the dataset in real time. The second half of this paper describes the data compression scheme implemented to reduce the size of the time-varying dataset. Additionally, rapid data access and issues regarding the real-time data management aspects are discussed. Analysis of the performance of the model is made and preliminary comparisons with a traditional analytical wake vortex model are discussed.

Spencer, T. L. and Trani, A. A.

"PREDICTIVE MODELS OF DEPARTURE AND ARRIVAL OCCUPANCY TIME AND TAKE-OFF DISTANCE"

AIAA Paper 2018-4141, June 2018, Atlanta, GA.

Values of departure and arrival runway occupancy time and take-off distance are commonly used parameters for many airport and air transportation simulation models. However, these data are typically found either aggregated by weight or wake class or are otherwise unavailable. Furthermore, field collection of these data can be prohibitively time-consuming and expensive. To fill this data gap, we present predictive models of departure runway occupancy time, take-off distance, and arrival runway occupancy time. Through comparison of multiple frameworks, we find that the Bayesian modeling framework offers the strongest predictive performance. Using hierarchical Bayesian regression, the models developed cover 85 individual aircraft types and address the considerable variability present in the arrival and departure performance of different aircraft. The additional benefit of the Bayesian model is its output of probability distributions, which many simulation models readily accept.

Spentzos, A., Barakos, G. N., Badcock, K. J., Richards, B. E., Coton, F. N., Galbraith, R. A. McD., Berton, E. and Favier, D.

"COMPUTATIONAL FLUID DYNAMICS STUDY OF THREE-DIMENSIONAL DYNAMIC STALL OF VARIOUS PLANFORM SHAPES"

Journal of Aircraft, Vol. 44, No. 4, July-August 2007, pp. 1118-1128.

Numerical simulation of 3-D dynamic stall has been undertaken using computational fluid dynamics. As a first step, validation calculations have been performed for cases in which experimental data were available. Although the amount and quality of the experimental data available for 3-D dynamic stall does not match what is available for 2-D cases, the computational fluid dynamics was found capable of

predicting this complex 3-D flow with good accuracy. Once confidence on the computational fluid dynamics method was established, further calculations were conducted for several wing planforms. The calculations revealed the detailed structure of the 3-D dynamic stall vortex and its interaction with the tip vortex. Remarkably, strong similarities in the flow topology were identified for wings of very different planforms.

Spillman, J. J.

"THE USE OF WING TIP SAILS TO REDUCE VORTEX DRAG"

Aeronautical Journal, Vol. 82, September 1978, pp. 387-395.

Small cambered and twisted surfaces, called sails, fitted to the wing tips of an aircraft can reduce its lift-dependent drag by up to 30 percent. Flight tests on a Paris aircraft show a 25 percent increase in maximum lift-drag ratio. Three or four sails per wing tip, each having a span of about a quarter of the wing tip chord and a root chord of about 16 percent of that of the wing tip seem to give the greatest vortex drag reductions when fitted, almost horizontally, outboard of the rear half of the wing tip. The sails need to be set in a spiral array round the tip, each sail being further away from the top surface of the wing, by 15 degree or more, than the sail in front of it. The sails need to turn the air smoothly from the spiral flow from lower to upper surface round the tip to a near streamwise direction. This requires the root sections of the sails to have circular arc camber lines bringing the tangent to the camber line at the nose of the sail more nearly into line with the local flow direction at positive wing incidences.

Spillman, J. J. and Allen, J. E.

"THE USE OF WING TIP SAILS TO REDUCE VORTEX DRAG"

Report No. 38, 1977, Cranfield Institute of Technology, Cranfield, Bedford, UK.

Windtunnel measurements of the flow around the tip tanks of a model of a Morane-Saulnier Paris aircraft have been used to design cambered and twisted auxiliary surfaces, each with only 0.4 to 0.6 percent of the wing area, which unwound the tip vortices formed at the incidence and in so doing experienced a thrust, effectively reducing the vortex drag. Flight tests on a Paris aircraft showed that three such sails per tip tank increased the effective aspect ratio of the wing by over 40 percent. The increase in the overall lift-drag ratio at a lift coefficient of 0.35 was 21 percent and the maximum lift-drag ratio increased from 12.5 to 15.8. More recent wind tunnel tests have shown that sails have a similar effect when fitted to plain wing tips. The results suggest that three or four sails spiraled round the rear half of each wing tip will give best results. These encouraging results suggest that far more wind tunnel, flight and design work should be done to realize the potential savings in drag and fuel.

Spilman, D. R. and Stengel, R. F.

"JET TRANSPORT RESPONSE TO A HORIZONTAL WIND VORTEX"

J. Aircraft, Vol. 32, No. 3, May-June 1995, pp. 480-485

The dynamic response of a twin-jet transport aircraft encountering a single-axis wind vortex on final approach to landing is investigated. Dynamic simulations are used to determine the effects of vortex strength, vortex length, lateral entry position, vertical entry position, and encounter incidence angle on the aircraft roll response parameters. Maximum roll rate and roll angle increase proportionally with vortex strength and vortex length, until a 'saturation length' is reached. Roll response is highly dependent on entry location: changes in lateral entry position affect maximum roll angle while changes in vertical entry position affect maximum roll rate. Peak roll rate and roll angle obtain their largest values at near-zero incidence angles. The response is highly dependent on the precise initial conditions of the encounter - even small variations from this initial condition cause significant changes in aircraft roll response.

Spitzer, E. A.

"OPERATIONAL SYSTEM GUIDELINES FOR VORTEX ADVISORY SYSTEM"

FAA-RD-79-20, April 1979, DOT Transportation Systems Center, Cambridge, MA

The phenomenon of wake vortices has introduced a major operational constraint on airport operations, resulting in a reduction of runway capacities. Increased knowledge about the behavior of wake vortices has resulted in the development of a model of vortex behavior as a function of meteorological conditions. Based on this vortex behavior model, a Vortex Advisory System (VAS) has been designed and built. The VAS measures the primary meteorological parameter (wind) which affects vortex behavior and indicates to controllers via displays when conditions are such that more efficient runway use is possible. A detailed description of the VAS and guidelines for an operational system are given.

Spitzer, E. A.

"PROJECT SOCRATES"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 129-132.

Various environmental and man-made atmospheric disturbances (such as windshear, microbursts, clear air turbulence and wake vortices) have proven hazardous to aviation safety. Those atmospheric phenomena also represent mechanisms known to generate low frequency and infrasonic sound. These sonic emissions arise in the form of passive broadband sound sources having signatures that can be detected, classified, located, and tracked over extreme stand-off distances from a passive receiver through acoustic array and signal processing. Short optical path forms of acoustic-optic sensing devices can detect, classify, locate, and track the acoustic signatures. These infrared laser-based forms of acoustic-optic remote sensors are called a Sensor for Optically Characterizing Ring-eddy Atmospheric Turbulence Emitting Sound (SOCRATES) system. The SOCRATES system provides a remote-sensing set or line array of virtual microphones. Phase I of the program is to focus on the detection of wake

vortices and the goal is to prove the viability of the technology. A testbed configuration is to be installed at the Volpe Center JFK vortex test site, so that concurrent data from the Volpe wind line sensors can be used to validate the SOCRATES sensor for wake detection. Phase II of the program is a detailed theory and modeling effort. Preliminary measurements at JFK have identified a passive broadband spectral hump centered around 50 Hz which is thought to be representative of wake vortex noise.

Spitzer, E. A., Hallock, J. N. and Wood, W. D.

"STATUS OF THE VORTEX ADVISORY SYSTEM"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 326-334

A Vortex Advisory System is currently undergoing tests at the Chicago O'Hare International Airport. By measuring the wind magnitude and direction with respect to a runway heading, the VAS indicates via a display when aircraft separations could be safely reduced to three nautical miles for all landing aircraft. The paper presents the rationale for the system, the concept, the system design, how data are being acquired to check the operation of the system, and the test results to date.

Spitzer, E. A., Hallock, J. N., Burnham, D. C. and Rudis, R. P.

"PAST WAKE VORTEX INVESTIGATIONS AND DYNAMIC SPACING SYSTEMS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 45-60

A review of past wake vortex investigations is divided into the early years (late 1960's to early 1970's), the active years (mid-1970's to early 1980's), the lean years (mid-1980's to early 1990's), and the current years (early 1990's to the present). Vortex motion and decay information is highlighted to summarize the current state of knowledge as gleaned from the many past data collection programs. Dynamic spacing systems defined in the 1970's and 1980's are described (Vortex Advisory System (based on wind alone), Vortex Warning System (based on wind and vortex tracking), Wake Vortex Avoidance system (based on wind and wind forecasting, vortex tracking, vortex strength, and Air Traffic Control interfaces), and a Parallel Runway Vortex Advisory System (based on wind, wind forecasting, and vortex tracking)).

Spitzer, E. A., Rees, F., VonWinkle, W. and Williams, R.

"AN OVERVIEW OF PROJECT SOCRATES"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

Project SOCRATES is a research and development project aimed at addressing air safety and airport productivity through application of advanced technologies previously investigated for the U.S.

Department of Defense. The basic premise is remote detection and localization of acoustic signatures from man-made and natural atmospheric turbulence. An acoustic-optic technology is used to sense low frequency sound that has propagated from the atmospheric hazard to an optical sensing beam. This presentation will describe the basic sensing concept as well as the current effort to demonstrate concept feasibility for detection of sound generated by aircraft wake vortices. Results from measurements taken at JFK airport will be presented. Subsequent efforts to develop an array of sensors and the processing to achieve interference reduction and sound source localization will also be described. The long-term view is to integrate this novel sensing technology with appropriate air safety systems to enhance overall capability and effectiveness.

Spitzer, E. A., Rudis, R. P., Hallock, J. N. and Greene, G. C.

"WINDLINE FOR PARALLEL RUNWAY OPERATIONS AT SFO"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

Wake turbulence poses a potential problem for side-by-side approaches to close-spaced parallel runways (229 m apart at SFO), particularly when the ceiling is too low to permit visual operations. The wake encounter risk depends upon the crosswind and the longitudinal displacement of the aircraft pair. The SFO windline tracks landing wakes generated over the first 650 m of the runway, a region where few prior wake measurements have been made.

Spreiter, J. R. and Sacks, A. H.

"A THEORETICAL STUDY OF THE AERODYNAMICS OF SLENDER CRUCIFORM-WING ARRANGEMENTS AND THEIR WAKES"

NACA TR-1296, January 1957, Langley Aeronautical Lab., Langley Field, VA

A theoretical study is made of some cruciform-wing arrangements and their wakes by means of slender-body theory. The basic ideas of this theory are reviewed and equations are developed for the pressures, loadings, and forces on slender cruciform wings and wing-body combinations. The rolling-up of the vortex sheet behind a slender cruciform wing is considered at length and a numerical analysis is carried out using 40 vortices to calculate the wake shape at various distances behind an equal-span cruciform wing at a 45-degree bank. Analytical expressions are developed for the corresponding positions of the rolled-up vortex sheets using a 4-vortex approximation to the wake, and these positions are compared with the positions of the centroids of vorticity resulting from the numerical analysis. The agreement is found to be remarkably good at all distances behind the wing. Photographs of the wake as observed in a water tank are presented for various distances behind a cruciform wing at a 0 degree and a 45-degree bank. For a 45-degree bank, the distance behind the wing at which the upper two vortices pass between the lower two is measured experimentally and is found to agree well with the 4-vortex analysis. The calculation of loads on cruciform tails is considered in some detail by the method of reverse flow, and equations are developed for the tail loads in terms of the vortex positions calculated in the earlier analyses.

Spreiter, J. R. and Sacks, A. H.

"THE ROLLING UP OF THE TRAILING VORTEX SHEET AND ITS EFFECT ON THE DOWNWASH BEHIND WINGS"

J. Aeronautical Sciences, Vol. 18, No. 1, January 1951, pp. 21-32

The motion of the trailing vortices associated with a lifting wing is investigated by theoretical and visual-flow methods for the purpose of determining the proper vortex distribution to be used for downwash calculations. This involves the study of the rolling up and displacement of the trailing vortex sheet and the development of the cores of the rolled-up vortices. Both subsonic and supersonic speeds are considered in the analysis.

Squire, H. B.

"THE GROWTH OF A VORTEX IN TURBULENT FLOW"

ARC-16666, March 1954, Imperial College, London, England

The growth of a line vortex with time and the spread of a trailing vortex behind a wing due to turbulence are considered. It is shown that the eddy viscosity for this type of motion may be taken to be proportional to the circulation round the vortex and the solution is then similar to the solution for the growth of a vortex in laminar flow. The method is applied to calculate the distance behind a wing for which the trailing vortices will touch one another.

Squire, H. B.

"THE GROWTH OF A VORTEX IN TURBULENT FLOW"

Aero. Quarterly, Vol. 16, August 1965, pp. 302-306

The growth of a line vortex with time and the spread of a trailing vortex behind a wing due to turbulence are considered. It is shown that the eddy viscosity for this type of motion may be taken to be proportional to the circulation around the vortex and the solution is then similar to the solution for the growth of a vortex in laminar flow. The method is applied to calculate the distance behind a wing for which the trailing vortices will touch one another.

Sreedhar, M. K. and Ragab, S. A.

"LARGE EDDY SIMULATION OF A LONGITUDINAL VORTEX"

AIAA Paper No. 1994-0529, Reno, NV, January 1994.

Temporal large-eddy simulation is used to study the transitional and turbulent structure of stationary longitudinal vortices. Simulations are obtained for a high Reynolds number and at a low subsonic Mach number. The dynamic eddy-viscosity model is utilized to model the subgrid-scale stress tensor. Emphasis is given to the evolution of large-scale structures due to centrifugal instability and their subsequent breakdown into turbulence. When the vortex is unstable, ring-shaped structures appear around the vortex core. These structures interact with the core exchanging angular momentum between the core and the surroundings, which causes the decay of the mean tangential velocity. The turbulent kinetic energy of the initial disturbance increased rapidly and then a period of slow decay prevailed. The mean circulation profile showed good agreement with the universal inner profile of Hoffman and Joubert at the time of maximum turbulent kinetic energy.

Srigrarom, S.

"VORTEX BREAKDOWN SUPPRESSION BASED ON SELF-INDUCTION MECHANISM THEORY"

AIAA Paper No. 2000-0017, Reno, NV, January 2000

This study provides evidence to support an explanation of the phenomena of vortex breakdown proposed recently. The vortex breakdown is a phenomenon observable over a delta wing, where the vortex filament emanating from the apex suddenly enlarges and takes either spiral or bubble forms. The 'self-induction' mechanism due to the confined shear layer within the vortex filament is confirmed as the prime cause of the 'pile-up' effect of the vortices, and this leads to the vortex breakdown phenomena. Although, the 'self-induction' mechanism is unavoidable, the 'pile-up' effect can be avoided by changing the straightness of the vortex filament to a curved path. This reduces induction, which prevents the 'pile-up' of vortices (the threshold process of the vortex breakdown phenomena). In this study, we have modified the straight path of the vortex filament by two methods: 1) by changing the straight leading edge to a sinusoidal contour, and 2) by placing excrescence on the upper surface of the wing. Both methods lead to the absence of vortex breakdown, up to angle of attack of 35 degrees. Laser-induced fluorescence flow visualization images are presented together with the ordinary dye-injection flow visualization images. Digital particle image velocimetry results are also included to emphasize, upon the suppression of vortex breakdowns, the absence of backflow and the absence of a vorticity sign change, which are well-known criteria for the indication of vortex breakdown. A model analysis based on the proposed 'self-induction' model is also included.

Srinivasan, G. R., McCroskey, W J., Baeder, J. D. And Edwards, T.

"NUMERICAL SIMULATION OF TIP VORTICES OF WINGS IN SUBSONIC AND TRANSONIC FLOWS"

AIAA Paper No. 1986-1095, May 1986, Atlanta, GA.

A multi block zonal algorithm which solver the thin-layer Navier-Stokes and the Euler equation is used to numerically simulate the formation and roll-up of the tip vortex in both subsonic and transonic flows. Four test cases which used small and large aspect ratio wings gave been considered to examine the influence of the tip-cap shape, the tip-platform and the free-stream Mach number. It appears that

both the tip-platform and the tip-cap shape have some influence on the formation of the tip vortex, but its subsequent roll-up seems to be more influenced by the tip-platform shape. In general, a good definition of the formation and the roll-up of the tip vortex has been observed for all the cases considered here. Comparisons of the numerical results with the limited, available experimental data show good agreement with both the surface pressures and the tip-vortex strength.

Srinivasan, G. R., McCroskey, W. J., Baeder, J. D. and Edwards, T. A.

"NUMERICAL SIMULATION OF TIP VORTICES OF WINGS IN SUBSONIC AND TRANSONIC FLOWS"

AIAA Journal, Vol. 26, No. 10, October 1988, pp. 1153-1162

A multiblock zonal algorithm is used to solve numerically the thin-layer Navier-Stokes and the Euler equations for simulating the flowfields of isolated wings, with particular emphasis on understanding the formation and roll-up of tip vortices in subsonic and transonic flows. Four test cases consisting of wings of different planforms have been considered to examine the influence of the tip-cap shape, tip planform, and freestream Mach number. Comparison of the numerical results with the available experimental data shows good agreement for the surface pressures in the regions where the flow is attached or mildly separated. However, discrepancies exist in regions of massive shock-induced separation in transonic flow and in the immediate vicinity of the wing tip in subsonic flow. In general, a good definition of the formation and roll-up of the tip vortex is demonstrated for all the cases considered here, subject to the coarseness of the grid in the far field. Finally, the calculated lift, drag, and pitching-moment coefficients agree well with the experimentally determined values, where available.

Sroga, J. T., Eloranta, E. W. and Barber, T.

"LIDAR MEASUREMENTS OF WIND VELOCITY PROFILES IN THE BOUNDARY LAYER"

Journal of Applied Meteorology, Vol. 19, May 1980, pp. 598-605.

A lidar technique for measuring wind in the atmospheric boundary is presented. Inhomogeneities in ambient aerosol content are used as tracers of the wind. This technique yields both horizontal components of the wind and the wind velocity variance. These results are achieved using a model which assumes an isotropic Gaussian distribution of turbulent velocities. Experimental results comparing lidar wind measurements with winds derived from radar-tracked pilot balloons and tower-measured anemometers show good agreement. Wind measurements have been obtained at slant range distances up to 6.5 km.

St. John, O. B.

"COLLECTION OF OPERATIONAL DATA ON WAKE VORTEX INCIDENTS IN THE UK"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 6-10

Data relating to pilots' reports of a total of over 300 incidents have been collated and analyzed covering a 5-year period.

Stack, J.

"EXPERIMENTAL INVESTIGATION OF ROTOR VORTEX WAKES IN DESCENT"

ICAS 2004, Paper 2004-2.9.3, Aug.-Sept. 2004, Yokohama, Japan.

An experimental study is performed on a three-bladed rotor model in a water tow tank. The rotor's rotational velocity, the rotor plane angle of attack, and the carriage speed are all varied in order to simulate a wide range of rotorcraft operating states. The focus is on descent speeds and angles where the rotor is operating in or near vortex ring state. Circulation Reynolds numbers are of order 100,000 and chord Reynolds numbers are of order 10,000. Flow visualization is done using air bubbles and fluorescent dye injected tangentially from the blade tips to mark the vortex core, showing the development of both short-wave and long-wave instabilities on the helical vortices in the wake. Strain gages are used to record transient loads, allowing a correlation between the rotor thrust performance and the development of the vortex wake. The data indicate that as the instability develops, the adjacent vortices merge and form thick vortex rings, especially during descent. Periodic shedding of vorticity from the wake associated with vortex ring state is observed, resulting in peak-to-peak thrust fluctuations of up to 95% of the mean and occurring at regular intervals of 20 - 50 rotor revolutions, depending on flow parameters.

Stack, J.

"EXPERIMENTAL INVESTIGATION OF ROTOR VORTEX WAKES IN DESCENT"

AIAA Paper No. 2004-0297, Reno, NV, January 2004

An experimental study is performed on a three-bladed rotor model in a water tow tank. The blade pitch and rotational velocity, the rotor plane angle of attack, and the carriage speed are all varied to simulate a wide range of rotorcraft operating states. The focus is on descent speeds and angles where the rotor is operating in or near vortex ring state. Circulation Reynolds numbers are of order 100,000 and chord Reynolds numbers are of order 10,000. Flow visualization is done using air bubbles and fluorescent dye injected tangentially from the blade tips to mark the vortex core, showing the development of both short-wave and long-wave instabilities on the helical vortices in the wake. Strain gages are used to record transient loads, allowing a correlation between the rotor thrust performance and the development of the vortex wake. The data indicate that as the instability develops, the adjacent vortices merge and form thick vortex rings, especially during descent. Periodic shedding of vorticity from the wake associated with vortex ring state is observed, resulting in peak-to-peak thrust fluctuations of up to 95% of the mean and occurring at regular intervals of 20 - 50 rotor revolutions, depending on flow parameters.

Stack, J. A.

"AN EXPERIMENTAL INVESTIGATION OF THE VORTEX WAKES OF HOVERING AND DESCENDING ROTORS"

PhD Thesis, 2006, University of California, Berkeley, CA.

Two sets of experiments are performed on a three-bladed rotor model, one in a towing tank to simulate descent, and the other in a stationary tank to simulate hover. The rotor's rotational speed, collective pitch angle, descent angle, and descent speed are all varied, simulating a wide range of rotorcraft operating states. For this work, circulation-based Reynolds numbers are of order 100000 and chord-based Reynolds numbers are of order 10000. The focus of the first set of experiments is on descent speeds and angles where the rotor is operating in or near vortex ring state. Simultaneous flow visualization and thrust measurement allow the rotor's performance to be correlated to the development of the vortex wake. Periodic shedding of vorticity from the wake associated with vortex ring state is observed, resulting in peak-to-peak thrust fluctuations of up to 95 percent of the mean and occurring at regular intervals of 20-50 rotor rotations with the oscillation period exhibiting a power law dependence on the advance speed and varying inversely with the collective angle. The hover experiments use particle image velocimetry and flow visualization to analyze the development of the wakes from either rectangular planform rotor blades or blades with triangular flaps attached near the blade tips. The dynamics of the two wakes differ substantially, with short-wave instabilities observed developing on the tip vortices of both wakes, while a long-wave instability develops only in the wake of the rectangular blades. The rectangular blade wake also decays somewhat more rapidly than the triangular-flap blade wake. While the wake can be altered significantly through modifications to the blade planform geometries, the trajectories of the tip vortices are not significantly affected by varying the rotor speed or collective angle. The effects of the experimental techniques employed here on the flow are also explored, with the injection of fluid from the blade tips in flow visualization experiments having a particularly strong effect on the strengths of the tip vortices.

Stack, J., Caradonna, F. and Savas, O.

"FLOW VISUALIZATION AND PARTICLE IMAGE VELOCIMETRY ANALYSIS OF ROTOR VORTEX WAKES"

American Physical Society, 57th Annual Meeting Division of Fluid Mechanics, Nov. 2004, Seattle, WA.

An experimental study is performed on a three-bladed rotor model in a stationary water tank, simulating a helicopter rotor operating in hover at Reynolds numbers of order 10,000. Flow visualization is done by injecting air bubbles and fluorescent dye tangentially from the blade tips to mark the vortices, showing the development of both short-wave (sinuous) and long-wave (leapfrogging) instabilities on the helical vortex filaments in the wake. The flow images show that as the instabilities develop, adjacent vortices merge and form thick vortex rings as quickly as half a rotor diameter downstream of the rotor disk. Particle image velocimetry data demonstrate the existence of the short-wave instability, evidenced by oscillations in the adjacent vortex core separation distance. At the same time, the long-wave instability is also apparent, as the vortices can be seen orbiting each other prior to merger. The circular axis and the moments of vorticity distribution are used to analyze

the kinematics of vortex filament triads during formation, instability, and merger phases. Comparison of flow visualization and vorticity movies, however, shows interesting differences in the vortex merger process, possibly as a result of axial flow in the vortex cores.

Stack, J., Caradonna, F. and Savas, O.

"EXPERIMENTAL STUDY OF ROTOR WAKES IN DESCENT"

American Physical Society, 55th Annual Meeting Division of Fluid Mechanics, Nov. 2002, Austin, TX.

An experimental study is performed on a three-bladed rotor model in a water tow tank. The blade pitch and rotational velocity, the rotor plane angle of attack, and the carriage speed are all varied in order to simulate a wide range of rotorcraft operating states. Circulation Reynolds numbers are of order 100,000 and blade Reynolds numbers are of order 10,000. Flow visualization is done using air bubbles or dye injected from the blade tips to mark the vortex core, showing the development of an instability on the helical vortices in the wake. PIV data provide quantitative measures of the flow field as the wake develops. Strain gages are also used to record transient load measurements, allowing a correlation to be made between the rotor performance and the development of the vortex wake. The data so far indicate that as the instability develops, the adjacent vortices merge and form thick vortex rings, especially during descent. The vorticity spreads and is periodically shed from the wake, resulting in significant fluctuations in the rotor loading.

Stack, J., Caradonna, F. and Savas, O.

"FLOW VISUALIZATION AND EXTENDED THRUST TIME HISTORIES OF ROTOR VORTEX WAKES IN DESCENT"

American Physical Society, 56th Annual Meeting Division of Fluid Mechanics, Nov. 2003, Easrt Rutherford, NJ.

An experimental study is performed on a three-bladed rotor model in a water tow tank. The blade pitch and rotational velocity, the rotor plane angle of attack (descent angle), and the carriage speed are all varied in order to simulate a wide range of rotorcraft operating states, with the focus being on descent speeds and angles where the rotor is operating in or near vortex ring state an area in which there is currently very little available data. Circulation and blade Reynolds numbers are of order 100000. Flow visualization is done by injecting air bubbles and fluorescent dye tangentially from the blade tips to mark the vortex core, showing the development of both short-wave (sinuous) and long-wave (leapfrogging) instabilities on the helical vortices in the wake. Strain gages are used to record transient loads, allowing a correlation between the rotor thrust performance and the development of the vortex wake. Test runs are performed for extended periods up to 500 rotor revolutions demonstrating the repeatability of the patterns of thrust variation. The data indicate that as the instabilities develop, adjacent vortices merge and form thick vortex rings, particularly during descent. Periodic shedding of these rings from the wake associated with vortex ring state is observed, resulting in peak-to-peak thrust fluctuations of up to 95 percent of the mean and occurring at regular intervals of

2050 rotor revolutions, depending on flow parameters. Preliminary particle image velocimetry data provide a quantitative measure of the entire rotor flow field for the case of a hovering rotor. The data yield additional information on the vortex filament instability, in particular the axial flow in the vortex cores.

Stack, J., Caradonna, F. X. and Savas, O.

"FLOW VISUALIZATIONS AND EXTENDED THRUST TIME HISTORIES OF ROTOR VORTEX WAKES IN DESCENT"

Proc. American Helicopter Society 4th Decennial Specialists' Conf. on Aeromechanics, Jan. 2004, San Francisco, CA.

An experimental study is performed on a three-bladed rotor model in two water tanks. The blade pitch, rotational velocity, descent angle, and descent speed are all varied to simulate a wide range of rotorcraft operating states, focusing on descent cases where the rotor is operating in or near vortex ring state -- an area in which there is currently very little available data. Flow visualization is done by injecting air bubbles and fluorescent dye tangentially from the blade tips to mark the vortex core, showing the development of both short-wave (sinuous) and long-wave (leapfrogging) instabilities on the helical vortices in the wake. Strain gauges are used to record transient loads, allowing a correlation between the rotor thrust performance and the development of the vortex wake. Reynolds numbers are of order 100,000 and test runs are performed for extended periods -- up to 500 rotor revolutions -- demonstrating the repeatability of the patterns of thrust variation. The data indicate that as the instabilities develop, adjacent vortices merge and form thick vortex rings, particularly during descent. Periodic shedding of these rings from the wake associated with vortex ring state is observed, resulting in peak-to-peak thrust fluctuations of up to 95 percent of the mean and occurring at regular intervals of 20-50 rotor revolutions, depending on flow parameters.

Starn, A. D.

"DOPPLER GLOBAL VELOCIMETRY MEASUREMENTS IN A WING FLOW FIELD WITH TIP BLOWING"

MS Thesis, 2004, West Virginia University, Morgantown, WV.

A two-component Doppler global velocimetry (DGV) system has been developed, improved, and tested. DGV is a non-intrusive optical velocity measurement technique. DGV measures the Doppler shift of the frequency of the light scattered by seed particles at a specific location. The velocity of the particles is related to the Doppler shift. DGV measurements were made in the WVU low speed wind tunnel on a turbulent jet and on a NACA 2412 airfoil model with and without tip blowing. The jet data generally agreed with previous measurements. The jet velocity error was generally within ± 2 -4 m/s. The offset error of up to ± 10 m/s was attributed to difficulties in cell calibration. The velocity data obtained from the airfoil measurements was limited to the regions of space where the gray levels were high enough to yield meaningful results. In these regions, the observed error was comparable to that of the jet.

Starr, J. W., Sernas, V. and Fletcher, L. S.

"AIRCRAFT VORTEX DETECTION USING DUAL LASER BEAMS"

J. Aircraft, Vol. 12, No. 2, February 1975, pp. 123-124

The note reports laboratory experiments on a dual laser beam vortex detection system which in practice could be relatively simple, insensitive to heating effects, and would not interfere with visibility or normal airport functions. The laser beams are directed along the length of the runway and are used in pairs to detect the difference in the deflection of the beams. The optical vortex detection system works on the same principal as a schlieren system in which the individual laser beams act as schlieren system beams which are cut off by their own knife edge.

Start, G. E. and Dickson, C. R.

"WINGTIP VORTEX DIAMETERS, TANGENTIAL SPEEDS AND HORIZONTAL TRANSPORT WITHIN THE FIRST 100 FEET ABOVE THE GROUND"

Report, September 1970, Air Resources Laboratories Field Research Office, Idaho Falls, Idaho.

The research supported in this study was part of a joint government and industry accelerated evaluation of the operational impact of wake turbulence produced by large jet aircraft. Data were collected through low altitude aircraft flybys of instrumented towers by Boeing 727 and 707 aircraft, a Douglas DC9, and a Convair 880. Aircraft induced air circulations were measured by hot film anemometry. Smoke visualized vortex circulations were filmed by FAA personnel to supplement the vortex measurements. The fundamental purpose of this data set is the provision of a quantitative estimate of vortex characteristics for FAA follow-on studies. These studies would attempt to relate these characteristics to the characteristics of the test aircraft, its flight configuration, and other relevant aerodynamic parameters. The tower measurements and calculated vortex characteristics are shown in several data tables and graphical depictions. The vortex characteristics presented are vortex size, basic shape, tangential speed versus radial distance, core diameter, age, speed of horizontal transport, separation of vortex pair centers, and supplemental measurements of atmospheric wind speeds and temperatures. A smaller vertical spacing of tower sensors, on the order of one foot, is necessary to better measure and better quantize the vortex core characteristics and the radial distribution of tangential speeds. Sequential tower measurements of the energy of circulation for the same vortex, combined with the appropriate micrometeorological measurements are needed to evaluate and quantize vortex decay in the atmosphere.

Stasenko, A. L and Vyshinsky, V. V.

"AIRCRAFT VORTEX WAKE - ENVIRONMENTAL AND FLIGHT SAFETY ASPECTS OF THE PROBLEM"

AIAA Paper No. 1998-5590, Anaheim, CA, September 1998

Vortices in fluid and gas are very stable formations featuring a slow mass, momentum, and energy exchange with surrounding atmosphere. The 'closure' of vortices, on the one hand, facilitates their visualization and, on the other hand, results in accumulating and for long retaining hot engine exhaust gases entrained into the vortices in the stage of their formation in the near jet-vortex wake behind an aircraft. The latter problem is closely related to the environmental impact of aviation, especially within airport areas and ozone layer of the Earth's atmosphere. In this paper the problem of light scattering by particulates arising during water vapor condensation, droplet coagulation or breakdown is considered. Numerical results are presented of gas dynamic and optical properties of the aerosol-containing wakes of the Boeing-747-type aircraft and of the prospective Russian second-generation supersonic civil transport.

Stasenko, A. L.

"PHYSICAL MODELS OF VISUALIZATION OF A CIVIL AIRCRAFT AEROSOL VORTEX WAKE IN THE AIRPORT VICINITY"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

At present, the interest of the scientific community seems to shift more and more to the problem of augmentation of the airport capacity and providing simultaneously the vortex wake safety. The most radical method to diminish the hazard from a heavy airliner vortex is to make it visible. The most convenient way to realize this method is to illumine the aircraft wake with a laser beam (in optical or IR wave-band).

Staufenbiel, R. and Vitting, T.

"FORMATION OF TIP VORTICES AND VORTEX WAKE ALEVIATION BY TIP DEVICES"

Proceedings 17th ICAS Congress, Stockholm, Sweden, September 1990, Vol. 1, pp. 279-291

Formation and structure of wing tip vortices as well as some methods of vortex wake alleviation are subjects of the paper. The formation of vortices is investigated theoretically and experimentally. For calculating the roll-up of vortices, a modified line vortex method is introduced using an amalgamation process which preserves important conservation laws. A comparison of experimental and theoretical data yields good agreement. In the second part of the paper, different ways of tip vortex dissipation have been tested such as destabilization of vortices, stimulation of vortex breakdown and redistribution of the vorticity in tip vortices. Experiments, carried out in the water tunnel, evaluated vortex structure as well as profiles of tangential and axial velocity components using LDV and flow visualization techniques.

Staufenbiel, R. and Vitting, T.

"ON AIRCRAFT WAKE PROPERTIES AND SOME METHODS FOR STIMULATING DECAY AND BREAKDOWN OF TIP VORTICES"

Vortex Flow Aerodynamics, AGARD-CP-494, July 1991, pp. 26-1 - 26-14

Investigations on the formation and structure of wing tip vortices are presented. A computational method for the time-dependent roll-up process is derived, which is based on the Biot-Savart approach with a particular technique of amalgamation which preserves energy, center of vorticity, and the second moment of vorticity distribution. The results are compared with laser Doppler velocimeter (LDV) measurements performed in a water tunnel. The influence of lift distribution on maximum circumferential velocity of trailing vortices is investigated. Moreover, some special devices for vortex wake alleviation were experimentally investigated to reveal the potential of three methods for vortex wake alleviation: (1) artificially destabilizing the vortex; (2) inducing breakdown of the vortex core; and (3) spreading and splitting the vorticity of trailing vortices.

Staufenbiel, R. W.

"STRUCTURE OF LIFT-GENERATED ROLLED-UP VORTICES"

J. Aircraft, Vol. 21, No. 10, October 1984, pp. 737-744

Widely used analytical models describing the structure of lift-generated vortices behind aircraft wings (e.g., models of Betz or Lamb) are generally not in acceptable agreement with experiments. The lack in conservation of vortical dispersion and rotational energy, which relates to the induced drag of the generating wing, is considered as a reason for this discrepancy. The model of Lamb is modified in a simple way to account for the conservation laws. These modifications yield a reduction in the core radius and a remarkable increase in the maximum tangential speed. A comparison with experiments is made and reasonable agreement is found. For the modification of the vorticity distribution in the Lamb model, the Kirchhoff-Routh function is used. This function is proportional to the rotational energy for a continuously spaced array of point vortices having the proper vorticity. The proposed model can be adapted to arbitrary vorticity distributions and, hence, wing loadings.

Steen, M. and Hecker, P.

"INVESTIGATING THE POTENTIAL FUTURE USAGE OF COMBINED AIRBORNE WAKE VORTEX PREDICTION MODELS AND MEASUREMENT SENSORS"

AIAA Paper 2018-3022, June 2018, Atlanta, GA.

As world-wide air traffic is constantly increasing, new possibilities are currently investigated and planned to restructure the airspace including a reduction of also enroute separations for increasing the overall airspace capacity. As soon as enroute separations are reduced to a minimum, enabled by navigational means, the wake vortex phenomenon needs to be considered for separation, because the needed separations due to a generated wake vortex might be larger under certain atmospheric conditions than the separations enabled by navigational accuracy and integrity. As this evolution had been predictable, attempts have been made over the last years to introduce airborne methods to predict the wake vortex behavior of a preceding aircraft. Additionally, some research focus has also been on the usage of airborne sensors to detect the wake vortex for the purpose of wake vortex

encounter avoidance, but also to act as a safety net by feeding information on the wake vortex induced lift distribution to the flight controls in case a wake vortex is in almost vicinity and an encounter is not avoidable. For wake vortex avoidance, both a wake vortex prediction and a detection are applicable independently, but a combination of both would take advantage of their complementarity. Such a combination of wake vortex prediction by means of a wake vortex model and wake vortex detection by means of an airborne sensor would be the optimum during cruise to ensure reduced separations on the one hand side, and safe wake vortex separations on the other hand. For such a combined system, this paper will introduce the needed theoretical background and will show possible future applications for envisaged new operational concepts. A combined airborne wake vortex prediction and detection system is being investigated by means of a simulation environment, and potential improvements in prediction accuracy in the presence of ambient uncertainties are presented.

Steen, M., Schonhals, S. and Hecker, P.

"COLLABORATION OF WAKE VORTEX MODELS AND SENSORS IN MODERN AVIONICS SYSTEMS"

Digital Avionics Systems Conf., Oct. 2009, Orlando, FL, pp. 1.C.1-1-9.

Today's airport capacity is severely limited by separation of approaching and to a lesser extent departing aircraft to ensure that following aircraft do not encounter the wake vortex generated by the preceding one. The encounter of wake vortices, especially during take-off and landing, can cause critical or even catastrophic flight situations for the succeeding plane. Historically, the wake vortex separation standards are based on a 'worst-case-scenario'.

Steen, M., Schonhals, S., Polvinen, J., Drake, P., Cariou, J.-P., Dolfi-Bouteyre, A. and Barbaresco, F.

"CANDIDATE TECHNOLOGIES SURVEY OF AIRPORT WIND & WAKE-VORTEX MONITORING SENSORS"

9th Innovative Research Workshop & Exhibition, Dec. 2010, Bretigny-sur-Orge, France.

A new generation of low-cost sensors has recently emerged, boosted by technological breakthroughs. These sensors will be key building blocks of critical Wake Vortex Advisory System and Integrated Terminal Weather Systems for Airports. We propose to make a survey of candidate technologies based on invited international guest keynote speakers and experts from Europe, USA and Asia for WAKENET-3 Europe workshop.

Steen, M., Stanisak, M. and Hecker, P.

"IN-FLIGHT TESTING OF AIRBORNE LIDAR FOR WAKE VORTEX DETECTION, CHARACTERIZATION AND TRACKING"

AIAA Paper 2014-2336, June 2014, Atlanta, GA.

Today wake vortex dependent spacing between aircraft is achieved by static distances for arrival but also for enroute. With the upcoming operational novelties foreseen in NextGen and SESAR like in-trail

procedures and aircraft self-separation, aircraft wake vortex encounter mitigation comes into focus especially for the enroute flight phase. For the localization of aircraft wake vortices generated by surrounding aircraft, two possibilities exist in general: determining the position, movement, and strength by means of wake vortex model prediction and the detection by dedicated airborne sensors. While prediction is prone to uncertainties in model input quantities, airborne detection sensors like LIDAR are prone to a large scanning domain, adverse scanning geometry and challenging signal processing. To overcome the drawbacks of both model prediction and sensor detection, the Institute of Flight Guidance of the Technische Universitaet Braunschweig is planning to conduct flight trials with an airborne LIDAR equipment for wake vortex detection and tracking utilizing special prediction-detection fusion approaches. This paper describes the airborne LIDAR installation, the system layout, and the connection to the aircraft avionics for the steering of the LIDAR scanning.

Steger, J. L. and Kutler, P.

"IMPLICIT FINITE-DIFFERENCE PROCEDURES FOR THE COMPUTATION OF VORTEX WAKES"

AIAA Journal, Vol. 15, No. 4, April 1977, pp. 581-590

Implicit finite-difference procedures for the primitive form of the incompressible Navier-Stokes and the compressible Euler equations are used to compute vortex wake flows. The partial differential equations in strong conservation-law form are transformed to cluster grid points in regions with large changes in vorticity. In addition to clustering, fourth-order accurate, spatial difference operators are used to help resolve the flowfield gradients. The use of implicit time-differencing permits large time steps to be taken since temporal variations are typically small. Computational efficiency is achieved by approximate factorization. Both two-dimensional and preliminary three-dimensional calculations are described.

Steijl, R. and Hoeijmakers, H. W. M.

"THREE-DIMENSIONAL CO-OPERATIVE INSTABILITIES IN WAKE VORTEX PAIRS"

ICAS-2002-2.8.2, Toronto, Canada, September 2002

A numerical study is presented concerning three-dimensional cooperative instabilities in vortex pairs. A counter-rotating vortex pair can develop two fundamentally different types of instabilities: short-wavelength or elliptic instabilities and long-wavelength or Crow instabilities. The role of both types is considered in the decay of an aircraft vortex wake.

Steijl, R. and Hoeijmakers, H. W. M.

"THE DYNAMICS OF THE SHORT-WAVELENGTH INSTABILITY IN AIRCRAFT WAKE VORTEX PAIRS"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

This presentation focuses on the short-wavelength instability in a counter-rotating vortex pair. In aircraft wake vortex studies, this type of instability has not been studied as extensively as the long-wavelength instability. The dynamics of the long-wavelength, or Crow, instability forms a major aspect of the decay process of aircraft wake trailing vortices. In most visualization studies of aircraft trailing vortices, short-wavelength instability modes are not observed. Therefore, the contribution of this type of instability to the decay of trailing vortices is generally considered to be less important than that of the Crow instability. However, understanding the dynamics of the short-wavelength instability can be crucial in the design of (active) devices or methods that enhance the decay of trailing vortices. This paper studies the effect of Reynolds number, spacing of the vortex pair and axial wave number of the prescribed instability mode on the temporal evolution.

Steijl, R. and Hoeijmakers, H. W. M.

"HIGH-RESOLUTION SIMULATIONS OF CROW AND WIDNALL INSTABILITIES IN A VORTEX PAIR"

AIAA Paper No. 2001-1033, Reno, NV, January 2001

This paper describes simulations performed for both short-wavelength (Widnall) and long-wavelength (Crow) instabilities in counter-rotating line-vortex pairs. Both types of instabilities result from the mutually induced velocity of the two vortices and form fast-growing sinusoidal perturbations, at very different wavelengths: of the order of the vortex core radius for the Widnall instability and 5 to 10 times the initial vortex spacing for the Crow instability. The paper starts with a discussion of the governing equations and the numerical method used. Then, a study is presented for the long-wavelength instability, including an analysis of the spatial resolution of the simulation. The transfer of kinetic energy towards smaller scales as the development of the instability progresses, is studied, showing that the flow field is indeed well-resolved in the simulations. The short-wavelength instability simulations are initialized with an initial condition computed from a normal mode analysis of the linearized equations in cylinder coordinates. This procedure is discussed in some detail, followed by a presentation of preliminary results from a time-accurate simulation of the instability well into the regime in which non-linear effects become important.

Steijl, R. and Hoeijmakers, H. W. M.

"WAKE VORTEX SIMULATIONS USING A PARALLEL HIGH-ORDER ACCURATE NAVIER-STOKES SOLVER"

ICAS Paper 2000-6.5.3, August 2000, Harrogate, UK.

A well-known problem in the operation of commercial jet transports is the so-called 'wake vortex hazard.' This problem originates from the compact, strong vortices emanating from the wing tips which persist without much decay in their strength. The velocity field induced by these tip vortices forms a threat to following aircraft. Vortex wakes generally develop 3D instabilities of which the long-wavelength, or Crow, instability can often be observed as sinusoidal perturbations in aircraft contrails. The present paper describes a high-resolution algorithm for solving the Navier-Stokes equations

developed to numerically simulate these wake-vortex flows. Results obtained for an evolving long-wavelength instability in a vortex pair are discussed.

Steinhoff, J.

"COMPUTATION OF TWO DIMENSIONAL VORTEX SHEET ROLL UP"

ICAS 1984, September 1984, Toulouse, France.

We describe two methods to treat vortex sheets in a Lagrangian manner as a discontinuity, but to compute the rest of the flow using a fixed Eulerian grid. This way, we retain advantages of both schemes. The method is applied to the vortex sheet shed by an elliptically loaded wing, in the parabolized approximation. In this approximation, the vorticity is assumed to be normal to a two dimensional cross-stream computational plane. Thus the sheet is treated as a line across which the cross-stream velocity is discontinuous. The stream-wise variation of velocity is then neglected and time evolution of the line in the plane approximates the cross-stream variation as the sheet is followed downstream. The time-dependent problem is solved as follows: At each time step, the vortex line is first assumed to be fixed and a potential is computed on a grid such that the discontinuity across the line is maintained and Laplace's equation is satisfied everywhere else. Then, a velocity is computed along the line by interpolation from the grid. Finally, a forward Euler integration scheme is used to compute the new position of the line. The main approximation assumed is that of the radius of curvature of the line is much larger than the grid cell width. One method described is analogous to shock fitting and involves fitting the discontinuity. The other, presented previously, involves spreading the discontinuity over several grid cells, and is analogous to shock capturing. A numerical comparison of the two schemes is given.

Steinhoff, J. and Underhill, D.

"MODIFICATION OF THE EULER EQUATIONS FOR 'VORTICITY CONFINEMENT': APPLICATION TO THE COMPUTATION OF INTERACTING VORTEX RINGS"

Physics of Fluids, Vol. 6, No. 8, August 1994, 2738-274.

A new 'vorticity confinement' method is described which involves adding a term to the momentum conservation equations of fluid dynamics. This term depends only on local variables and is zero outside vortical regions. The partial differential equations with this extra term admit solutions that consist of Lagrangian-like confined vortical regions, or covons, in the shape of two-dimensional (2-D) vortex 'blobs' and three-dimensional (3-D) vortex filaments, which convect in a constant external velocity field with a fixed internal structure, without spreading, even if the equations contain diffusive terms. Solutions of the discretized equations on a fixed Eulerian grid show the same behavior, despite numerical diffusion. Effectively, the new term, together with diffusive terms, constitute a new type of regularization of the inviscid equations which appears to be very useful in the numerical solution of flow problems involving thin vortical regions. The discretized Euler equations with the extra term can be solved on fairly coarse, Eulerian computational grids with simple low-order (first- or second-)

accurate numerical methods, but will still yield concentrated vortices which convect without spreading due to numerical diffusion. Since only a fixed grid is used with local variables, the vorticity confinement method is quite general and can automatically accommodate changes in vortex topology, such as merging. Applications are presented for incompressible flow in 3D, where pairs of thin vortex rings interact and, in some cases, merge.

Stephan, A., Holzaepfel, F. and Misaka, T.

"SIMULATION OF AIRCRAFT WAKE VORTICES DURING LANDING WITH DECAY ENHANCING OBSTACLES"

ICAS 2014, September 2014, St. Petersburg, Russia.

Wake-vortex evolution during landing of a long-range aircraft is investigated in a turbulent environment. The simulations cover final approach, touchdown on the tarmac, and the evolution of the wake after touchdown. An ambient turbulent crosswind and headwind field is generated in a pre-simulation. The wake is initialized using a RANS-LES coupling approach. The aircraft in high-lift configuration with deployed flaps and slats is swept through a ground fixed domain. The fuselage turbulence is modeled as white noise. The further development of the vortical wake is investigated by large-eddy simulation until final decay. After touchdown wake vortices are subjected to strong three-dimensional deformations and linking with the ground. The down-wind vortex is strongly advected with the wind and decays quickly. End effects appear after touchdown and propagate along the wake vortices against the flight direction. They lead to a non-uniform circulation decay of the rolled-up wake vortices. Additionally, the effect of a plate line installed in front of the runway is studied with this method. The plates cause disturbances of the vortices propagating to either side and interacting with the end effects. The plate line further accelerates the vortex decay.

Stephan, A., Holzaepfel, F. and Misaka, T.

"AIRCRAFT WAKE VORTEX DECAY IN GROUND PROXIMITY -- PHYSICAL MECHANISMS AND ARTIFICIAL ENHANCEMENT"

AIAA Paper No. 2012-2672, June 2012, New Orleans, LA.

Aircraft wake vortex evolution in ground proximity is investigated numerically with large eddy simulations (LES). The simulations are performed with different modifications of the ground surface to trigger rapid vortex decay or to simulate the landing of an aircraft. The impact of environmental turbulence in terms of turbulent winds is considered, where well-resolved and wall-modeled LES are performed for low and high Reynolds number cases, respectively. To understand wake vortex decay mechanisms in ground proximity the interaction of primary and secondary vortices is thoroughly investigated. The results show that vortex decay is initiated and accelerated with obstacles at the ground. To optimize obstacle shape and size we show that we can achieve a similar effect with relatively small plates as with large block-shaped barriers. Concerning large Reynolds number we show that turbulence effects triggered by the ground cannot be modeled by a simple wall model. As a first approximation of landing, we use a ramp at the ground and show that the flow disturbances are like

the result of flat ground with obstacles. In particular, two kinds of so-called end effects are superposed: pressure waves in the vortex core and the propagation of the secondary vortex structure.

Stephan, A., Holzaepfel, F. and Misaka, T.

"TOWARDS REALISTIC SIMULATION OF WAKE-VORTEX EVOLUTION DURING LANDING WITH FLAT AND COMPLEX TERRAIN"

International Symposium on Turbulence and Shear Flow Phenomena (TSFP-8), August 2013, Poitiers, France.

The complete landing phase of a long-range aircraft is studied including final approach, touchdown at the tarmac and the development of the wake. In particular, end effects appearing after touchdown and propagating along the wake vortices as well as their interaction with a plate line in front of the run way are investigated. An aircraft model in high lift configuration with deployed flaps and slats obtained from a high-fidelity Reynolds-averaged Navier-Stokes simulation is used to simulate the final approach until touchdown. After the wake initialization a large-eddy simulation of the vortical wake is performed until decay. The flow field is analyzed and the interaction with the ground is studied. End effects appear after touch down. They lead to a circulation decay combined with a growth of the core radius to 300 percent. That effect propagates downstream. The plate line further accelerates the vortex decay reducing rapidly the circulation by another 25 percent of the initial circulation.

Stephan, A., Holzaepfel, F. and Misaka, T.

"HYBRID SIMULATION OF WAKE VORTICES OF LANDING AIRCRAFT IN A TURBULENT ENVIRONMENT"

15th European Turbulence Conference, August 2015, Delft, The Netherlands.

Wake-vortex evolution during landing of a long range aircraft is investigated in a turbulent environment. The simulations cover final approach, touchdown on the tarmac, and the evolution of the wake after touchdown. An ambient turbulent crosswind and headwind field is generated in a pre-simulation. The wake is initialized using a RANS-LES coupling approach. The further development of the vortical wake is investigated by large-eddy simulation until final decay.

Stephan, A., Holzaepfel, F. and Misaka, T.

"HYBRID SIMULATION OF WAKE-VORTEX EVOLUTION DURING LANDING ON FLAT TERRAIN AND WITH PLATE LINE"

International Journal of Heat and Fluid Flow, Vol. 49, 2014, pp. 18-27.

Wake-vortex evolution during approach and landing of a long-range aircraft is investigated. The simulations cover final approach, touchdown on the tarmac, and the evolution of the wake after touchdown. The wake is initialized using a high-fidelity Reynolds-averaged Navier-Stokes solution of the flow field around an aircraft model. The aircraft in high-lift configuration with deployed flaps and

slats is swept through a ground fixed domain. The further development of the vortical wake is investigated by large-eddy simulation until final decay. The results show the formation of a pronounced shear layer at the ground and an increase in circulation in ground proximity, caused by the wing in ground effect. Disturbances at disconnected vortex ends, so-called end effects, appear after touchdown and propagate along the wake vortices against the flight direction. They lead to a circulation decay of the rolled-up wake vortices, combined with a growth of the core radius to 300 percent of its initial value. After touchdown wake vortices are subjected to strong three-dimensional deformations and linking with the ground. The complete vortex evolution, including roll-up and decay, is accelerated in ground proximity. Additionally, the effect of a plate line installed in front of the runway is studied with this method. The plates cause disturbances of the vortices propagating to either side and interacting with the end effects. The plate line further accelerates the vortex decay, reducing the circulation rapidly by another 25 percent of its initial value.

Stephan, A., Holzaepfel, F. and Misaka, T.

"AIRCRAFT WAKE-VORTEX DECAY IN GROUND PROXIMITY -- PHYSICAL MECHANISMS AND ARTIFICIAL ENHANCEMENT"

Journal of Aircraft, Vol. 50, No. 4, July-/august 2013, pp. 1250-1260.

Aircraft wake-vortex evolution in ground proximity is investigated numerically by means of large-eddy simulations. The simulations are performed either with a flat ground or with different modifications to the ground surface to trigger rapid vortex decay. The impact of environmental turbulence in terms of turbulent wind is considered, where wall-resolved and wall-modeled large-eddy simulation are performed for low- and high-Reynolds-number cases, respectively. To understand wake-vortex decay mechanisms in ground proximity, the interaction of primary and secondary vortices is carefully investigated. We find that vortex decay can be initiated at an earlier time and substantially accelerated with obstacles at the ground. We explain the fundamental vortex dynamics describing five characteristics of the phenomenon and quantify the decay. We demonstrate that similar effects can be achieved, employing relatively small plates lines as opposed to the original large block-shaped barriers. The obstacles trigger two kinds of so-called end effects: pressure disturbances propagating within the vortex cores and secondary vortex structures propagating along the outside of the vortex cores.

Stephan, A., Holzaepfel, F. and Misaka, T.

"AIRCRAFT WAKE-VORTEX DECAY IN GROUND PROXIMITY -- PHYSICAL MECHANISMS AND ARTIFICIAL ENHANCEMENT"

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Stephan, A., Holzaepfel, F. and Zholtovski, S.

"THE EFFECT OF GUSTS ON AIRCRAFT WAKE VORTICES"

Aircraft Engineering and Aerospace Technology, Vol. 89, Issue 5, 2017, pp. 692-702.

This study aims to investigate the effect of gusts on aircraft wake vortices. Aircraft wake vortices present a potential risk to following aircraft, particularly during final approach and landing, as wake vortices may remain in the flight corridor for a long time. Wind and turbulence are key factors that influence the wake vortex evolution and the wake vortex generation in the aircraft. Flying through a gust influences the wake vortex roll-up process and its evolution. Note that vertical and lateral gusts may affect counter-rotating wake vortices differently. Both vortices influence each other by inducing a downward velocity. Disturbances may therefore lead to local vortex tilting and later to a complex three-dimensional deformation. This work uses two different hybrid Reynolds-averaged Navier-Stokes/large-eddy simulation (RANS-LES) approaches to investigate the effect of gusts on wake vortex evolution. In a one-way coupling, a pre-calculated RANS velocity field of the aircraft's near-field is being swept through an LES domain. The effect of a sine gust on the turbulent wake is modeled by manipulating the RANS-field accordingly. As a more sophisticated approach, the concept of a two-way coupling is being presented. Here an LES solver is bi-directionally coupled with an unsteady RANS (URANS) solver, exchanging values at every physical time step of the simulation. A one-way coupling approach of the LES code MGLET and the RANS code TAU is presented to simulate the gust effect on aircraft wake vortices. Additionally, the concept of the two-way coupling of these two codes incorporating a coupling module. The gust effect of wake vortices subjected to a crosswind can be simulated. The vortex physics is analyzed. Unexpected behavior like fast upwind vortex decay is revealed.

Stephan, A., Holzaepfel, F., Misaka, T., Geisler, R. and Konrath, R.

"ENHANCEMENT OF AIRCRAFT WAKE VORTEX DECAY IN GROUND PROXIMITY - EXPERIMENT VERSUS SIMULATION"

CEAS Aeronautical Journal, Volume 5, Issue 2, 2014, pp. 109-125

Aircraft wake vortex evolution in ground proximity is investigated experimentally in a water towing tank as well as numerically with wall-resolved large eddy simulation (LES). With these complementary

instruments the enhancement of wake vortex decay by obstacles introduced at the ground surface is analyzed. The experimental methods include time-resolved stereo particle image velocimetry (PIV) and vortex core visualization. For comparison with the experiment, the LES considers the turbulent wake of the strut holding the towed aircraft model. Wake vortex trajectories and circulation decay are compared at different distances from the obstacle. Tracers are employed to visualize the obstacle's effects on the vortex core in LES and experiment.

Stephan, A., Holzaepfel, F., Rohlmann, D. and Rudnik, R.

"HYBRID NUMERICAL SIMULATION OF THE JET-WAKE-VORTEX INTERACTION OF A CRUISING AIRCRAFT"

AIAA Paper 2018-2865, June 2018, Atlanta, GA.

The aircraft wake of an A320 aircraft from roll-up until decay is investigated with hybrid Reynolds averaged Navier-Stokes/Large-eddy simulation methods. The turbulent jet as well as the heat emission is included. The dynamics of the wake vortices interacting with the jet exhaust is investigated as well as the heat evolution in the wake. The results show that the jet engines influence the near field as well as the far field. They disturb the coherency of the wake particularly the relatively strong engine vortex is getting turbulent very fast. This leads to a slower decay of the entire system, as the Crow-instabilities are suppressed and develop later. The heat dissipates very fast. The descending vortex system leaves a vertical heat plume, where the maximal temperature is in the turbulent jet first, but is captured inside the vortex core for later vortex ages.

Stephan, A., Schräll, J. and Holzaepfel, F.

"NUMERICAL OPTIMIZATION OF PLATE-LINE DESIGN FOR ENHANCED WAKE-VORTEX DECAY"

Journal of Aircraft, Vol. 54, No. 3, May-June 2017, pp. 995-1010.

The design of plate lines as a ground mounted device for wake-vortex decay enhancement is investigated in this work. The most important design parameters, the aspect ratio and plate distance, are analyzed for the wake vortices generated by two aircraft: the A340 as well as the A380. Large-eddy-simulations (LES) are used to simulate the wake-vortex evolution in ground proximity for different parameter combinations. Fully rolled-up wake vortices are initialized using a Lamb-Oseen vortex model resembling the characteristics of the two aircraft. With the stochastic, so-called kriging method, estimates of the performance and respective probabilistic envelopes are given for the design parameter region, spanned by the large-eddy-simulation. The vortex circulation averaged over the rapid decay phase is taken as the objective function. The large-eddy-simulation parameters are selected in the vicinity of the expected optimum. An optimal parameter combination can be localized in the A340 case, as well as in the A380 case. For both cases, statistical relevance is provided. Moreover, it can be deduced that the optimal parameters for the A380 are also well suited for smaller aircraft like an A340.

Stephan, A., Schräll, J. and Holzaepfel, F.

"NUMERICAL OPTIMIZATION OF PLATE LINE DESIGN FOR ENHANCED WAKE-VORTEX DECAY"

AIAA Paper 2016-3135, June 2016, Washington, DC.

The design of plate lines as a ground mounted device for wake-vortex decay enhancement is investigated in this work. The most important design parameters, aspect ratio and plate distance, are analyzed for the wake vortices generated by two aircraft, the A340 as well as the A380. Large-eddy-simulations (LES) are used to simulate the wake-vortex evolution in ground proximity for different parameter combinations. Fully rolled-up wake vortices are initialized using a Lamb-Oseen vortex model resembling the characteristics of the two aircraft. With the stochastic, so-called Kriging method, estimates of the performance and respective probabilistic envelopes are given for the design parameter region, spanned by the LES. As the objective function vortex circulation, averaged over the rapid decay phase, is taken. The LES parameters are selected in the vicinity of the expected optimum. An optimal parameter combination can be localized in the A340 as well as in the A380 case. For both cases we provide statistical relevance. Moreover, we can deduce that the optimal parameters for the A380 are also well suited for smaller aircraft like an A340.

Stephenson, J. D., Selan, R. and Bandettini, A.

"A COMPARISON AT MACH NUMBERS UP TO 0.92 OF THE CALCULATED AND EXPERIMENTAL DOWNWASH AND WAKE CHARACTERISTICS AT VARIOUS HORIZONTAL TAIL HEIGHTS BEHIND A WING WITH 45 DEGREES OF SWEEPBACK"

NACA RM-A55D27a, June 1955, Langley Aeronautical Lab., Langley Field, VA

Wind-tunnel tests were conducted at Mach numbers from 0.25 to 0.92 to measure downwash and dynamic pressure in the region of the tail of a wing-fuselage-tail model having a wing with 45 degrees of sweepback, an aspect ratio of 5.5, and NACA 64A010 sections normal to the quarter-chord line. The data were analyzed to determine the origin and character of variations in the contribution of the horizontal tail to static longitudinal stability observed in tests of the model with the tail in various vertical positions. The spanwise distribution of downwash at the tail and the effect of tail height on downwash were not accurately predicted by a theory in which it is assumed that horseshoe vortices are distributed along the wing quarter-chord line and that there is no rolling-up of the vortex sheet. A somewhat improved prediction of the spanwise distribution of downwash was provided by an approximate theory based on the flow induced by a single swept vortex, but this theory still did not predict the large downwash at high angles of attack that were observed experimentally at the higher tail positions.

Stephenson, J. H., Mula, S. M., Tinney, C. E. and Sirohi, J.

"FAR WAKE ROTORCRAFT VORTEX TUMBLING"

AIAA Paper No. 2012-0425, January 2012, Nashville, Tennessee.

The far wake trajectory of the tumbling tip vortex of a reduced-scale, 1 m diameter, four-bladed rotor during hover is studied using vortex methods combined with a center of mass analysis approach. Measurements of all three components of the velocity field are acquired using a stereo PIV system synchronized to capture up to 800 degrees wake age of the vortex with 10-degree offsets during hover conditions. The nominal operating condition of the rotor is at a rotational speed of 1520 RPM, corresponding to $RE = 248,000$ with a chord length of 58.5 mm. The rotor was operated with a pitch of 7.2 ± 0.5 degrees. The far wake vortex tumbling phenomenon is captured and described. It is shown that tip vortices from two blades tumble through approximately 180 degrees of rotation before they coalesce. It is seen that the parent vortices are stronger than the daughter vortex, but due to vortex stretching the daughter vortex has a smaller radius with greater swirl strength. An accurate characterization and prediction of the trajectory of the far wake vortex tumbling can enhance the ability to predict and alleviate the resuspension of particles during brownout as well as provide a database for far wake validation of CFD codes.

Sternfeld, H., Jr. and Schairer, J. O.

"STUDY OF ROTOR BLADE TIP VORTEX GEOMETRY FOR NOISE AND AIRFOIL APPLICATIONS"

D8-2464-1A, December 1969, Boeing-Vertol, Philadelphia, PA

The application of a technique for making helicopter tip vortices visible in order to study the effect of the separation between the vortex and a rotor blade on the noise generated by the rotor system was the primary purpose of this program. A secondary objective was to evaluate analytical prediction of the vortex path. Mathematical analyses were developed to obtain blade-vortex separation from the motion picture films taken during the tests.

Stewart, E. C.

"A PARAMETRIC STUDY OF ACCELERATIONS OF AN AIRPLANE DUE TO A WAKE VORTEX SYSTEM"

NASA/TM-1999-208745, May 1999, NASA Langley Research Center, Hampton, VA

A study was conducted using strip theory to systematically investigate the effects of progressively more complete descriptions of the interaction of an airplane with a wake vortex system. The emphasis was in roll-dominant, parallel, vortex encounters. That is, the simulated airplane's longitudinal axis was nearly parallel to the rotation axis of the vortex system for most of the results presented. The study began with a drag-less rectangular wing in the flow field of a single vortex and progressed to a complete airplane with aerodynamic surfaces possessing taper, sweep, dihedral, and stalling and immersed in the flow field of a vortex pair in ground effect. The effects of the pitch, roll, and yaw attitudes of the airplane on the calculated accelerations were also investigated. The airplane had the nominal characteristics of a Boeing 757, and the vortex flow field had the nominal characteristics of the wake of a Boeing 767. The Burnham-Hallock model of a vortex flow field was used throughout the study. The data are presented mainly in terms of contours of equal acceleration in a two-dimensional area centered on the vortex pair and having dimensions of 300 feet by 300 feet.

Stewart, E. C.

"PILOTED SIMULATIONS STUDY OF WAKE ENCOUNTERS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 351-370

Results from preliminary simulation work at the Langley Research Center using the Visual Motion Simulator are presented. The purpose of the work was to develop an experimental procedure for a more comprehensive follow-on study using airline pilots. This preliminary work utilized NASA research pilots and consultants to define a 'worst-case' vortex encounter scenario at a fixed wake vortex strength and to develop a subjective rating scale to be used in the follow-on study. The worst-case scenario that was developed was a manual approach in poor visibility conditions with repeated, random wake vortex encounters having rapid onset rates and reversals. The rating scale developed used references and comparisons to the more-common atmospheric turbulence. The preliminary results indicated that under these worst-case conditions, only low-level wake strengths could be tolerated.

Stewart, E. C.

"A PILOTED SIMULATION STUDY OF WAKE TURBULENCE ON FINAL APPROACH"

AIAA Paper 1998-4339, Boston, MA, August 1998

A piloted simulation study has been conducted in a research simulator to provide a means to estimate the effects of different levels of wake turbulence on final approach. A worst-case methodology was used to ensure conservative estimates. Fourteen airline pilots voluntarily participated in the study and flew almost 1000 approaches. The pilots rated the subjective severity of the disturbances using a special rating scale developed for this study. Several objective measures of the airplane/pilot response to the simulated wake turbulence were also made. All the data showed a large amount of variation between pilots and to a lesser extent for a given pilot. Therefore, the data were presented at 50, 70, 90 percentile levels as a function of vortex strength. The data allow estimates of the vortex strength for a given subjective or objective response and vice versa. The results of this study appear to be more conservative than the results of previous studies.

Stewart, E. C.

"A COMPARISON OF AIRBORNE WAKE VORTEX DETECTION MEASUREMENTS WITH VALUES PREDICTED FROM POTENTIAL THEORY"

NASA TP-3125, November 1991, Langley Research Center, Hampton, VA

An analysis of flight measurements made near a wake vortex was conducted to explore the feasibility of providing a pilot with useful wake-avoidance information. The measurements were made with relatively low-cost flow and motion sensors on a light airplane flying near the wake vortex of a

turboprop airplane weighing approximately 90000 lb. Algorithms were developed which removed the response of the airplane which were due solely to the flow field of the vortex. These parameters were compared with values predicted by potential theory. The results indicated that the presence of the vortex could be detected by a combination of parameters derived from the simple sensors. However, the location and strength of the vortex cannot be determined without additional and more accurate sensors.

Stewart, E. C.

"FLIGHT-TEST EVALUATION OF A DIRECT-MEASUREMENT AIRBORNE WAKE-VORTEX DETECTION CONCEPT"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 44-1 - 44-26

Flight measurements of the flow field in an airplane wake vortex have been analyzed to determine the feasibility of developing the sensor technology for an airborne wake-vortex detection and avoidance system. The measurements were made with relatively low-cost instrumentation on a light airplane flying at small angles to the path of a 90,000 lb turboprop airplane. Algorithms were developed to isolate the effects of the wake vortex on the measurements and produce candidate wake vortex detection parameters. Video recordings of the light airplane relative to a smoke trail in the wake vortex were used to determine the separation distance of the light airplane to the wake vortex. The measured wake vortex detection parameters are compared to values predicted using potential theory. The results indicate that the presence of the wake vortex can be detected with relatively simple instrumentation at a distance of about one wing span of the generating airplane for the flaps retracted configuration and about one-half to three-fourths wing span for the flaps extended configuration. The location and strength of the wake vortex, however, cannot be determined uniquely without more sophisticated instrumentation. A short discussion of the effects on an operational system of guidance constraints, turbulence, wake vortex irregularities, and ground effect is also presented.

Stewart, E. C.

"A STUDY OF THE INTERACTION BETWEEN A WAKE VORTEX AND AN ENCOUNTERING AIRPLANE"

AIAA Paper No. 1993-3642, Monterey, CA, August 1993

An analytical study of the mutual interaction between a wake vortex and an encountering airplane has been conducted. The interaction was calculated based on conservation of angular momentum of the wake vortex and the encountering airplane in the roll axis. For the nominal conditions assumed in the study, the interaction reduced the roll response in the first second by 20 percent compared to the classical method of calculating the response. However, depending on the conditions assumed, the reduction varied from 0 to 30 percent which could be highly significant in determining separation standards for airplanes.

Stewart, M. B., Cohen, S. B. and Troesch, A. W.

"EXPERIMENTS WITH UNSTEADY, FREE SURFACE, THREE-DIMENSIONAL VORTICES IN A THERMALLY STABLE, STRATIFIED FLUID"

NRL Memorandum Report 6630, May 1990, Naval Research Laboratory, Washington, DC.

The unsteady characteristics of a vortex pair formed behind a delta wing airfoil at a negative angle of attack have been studied experimentally in a large towing tank with a stable density stratification. Measurements of the vortex pair's upward migration and visualizations of the vortex circulation were made using the hydrogen bubble technique with a laser sheet illumination in the transverse plane. Axial visualizations of the vortex migration and axial velocities at the vortex core were made using the hydrogen bubble technique with a diffuse light source. The effects of the rising vortices and their circulation on the free surface temperature field was recorded using an imaging infrared radiometer mounted over the free surface.

Stewartson, K. and Hall, M. G.

"THE INNER VISCOUS SOLUTION FOR THE CORE OF A LEADING-EDGE VORTEX"

J. Fluid Mech., Vol. 15, Part 2, February 1963, pp. 306-318

Hall proposed a simplified model for the vortex core formed over a slender delta wing at incidence by the rolling-up of the shear layer that separates from a leading edge. This model enabled an outer inviscid solution and an inner viscous solution for the core to be obtained from the equations of motion. However, the procedure used for the inner solution led to several defects: in particular, the matching of the inner and outer solutions seemed unsatisfactory. In the present paper the defects are avoided by using a different procedure. The first approximation, in the sense of boundary-layer theory, is sought. A solution, in special variables, is obtained which is in the form of an asymptotic expansion containing inverse powers of the logarithm of a Reynolds number. The leading terms of the expansion are computed, and the results confirm that the inner and outer solutions are properly matched.

Stickle, J. W. and Kelly, M. W.

"GROUND-BASED FACILITIES FOR EVALUATING VORTEX MINIMIZATION CONCEPTS"

Proceedings Wake Vortex Minimization Symposium, NASA, SP-409, 1977, pp. 129-156

To determine the feasibility of altering the formation and decay of aircraft trailing vortices through aerodynamic means, NASA used the test capabilities of two wind tunnels and two towing basins. This paper describes the facilities, common models, and measurement techniques that were employed in the evaluation of vortex minimization concepts.

Stifle, K. E. and Panton, R. L.

"EXPERIMENTS CONCERNING THE THEORIES OF VORTEX BREAKDOWN"

AIAA Paper No. 91-0736, Jan. 1991, Reno, NV.

An experimental project was undertaken to investigate the character of vortex breakdown with focus on the stagnation and wave guide theories of vortex breakdown. Three different wings were used to produce a trailing vortex which convected downstream without undergoing breakdown. Disturbances were then introduced onto the vortex using a moving wire to 'cut' the vortex. The development of upstream and downstream propagating disturbance waves was observed and the propagation velocities measured. A downstream traveling wave was observed to produce a structure similar in appearance to a vortex breakdown. An upstream traveling wave produced a moving turbulent region. The upstream disturbance moved into an axial velocity profile that had a wake-like defect while the downstream moving vortex breakdown moved against a jet-like overshoot. The longitudinal and swirl velocity profiles were documented by LDV measurement. Wave velocities, swirl angles, and swirl parameters are reported.

Stilma, T. and Veldhuis, L. L. M.

"INITIAL CFD-SURVEY OF TIPTURBINE-EFFECTS ON THE NEAR-FIELD DEVELOPMENT OF A WINGTIP VORTEX"

AIAA Paper No. 2000-3199, Denver, CO, August 2000

The behavior of the wingtip vortex under the influence of several different perturbations, introduced by a wingtip mounted turbine positioned in the vortex, is investigated in this paper. The research was conducted on the tip area of a wing with a NACA 0012 profile, using a Navier-Stokes solver with a second-order numerical scheme. The domain contained approximately 1,000,000 points, the wing was set at a 6-degree angle of incidence and a freestream Mach number of 0.25. The perturbations were prescribed in the numerical domain on a plane, positioned in the vortex, 0.25 chords behind the wing. Three different types of perturbations have been applied, including a shear layer, a static pressure jump, and a tangential velocity distribution, contra-rotating with respect to the wingtip vortex. The impact of a change of the radius of the turbine has also been evaluated. The impact of the tangential velocity perturbations has shown to be the largest, even more so when the turbine radius exceeds the vortex core radius. The application of the tangential velocities is responsible for a decrease of the crossflow energy level and will cause the vortex to break up into several distinct regions of concentrated vorticity. This effect will enhance the vortex decay and it is recommended that future research will focus on the optimization of the tangential velocity perturbations and its effects on the breakup of the vortex.

Stinebring, D. R., Farrell, K. J. and Billet, M. L.

"THE STRUCTURE OF A THREE-DIMENSIONAL TIP VORTEX AT HIGH REYNOLDS NUMBERS"

Journal of Fluids Engineering, Vol. 113, Sept. 1991, pp. 496-503.

The tip vortex structure of a three-dimensional hydrofoil at high Reynolds number was measured experimentally in both the 48 in. (1.22 m) diameter water tunnel and the 48 in. (1.22 m) wind tunnel at the Applied Physics Laboratory, Penn State. The flow on and near the hydrofoil was measured in both facilities using several flow visualization techniques and laser velocimetry. The downstream tip vortex was measured with a three-component laser velocimeter at several streamwise positions. A detailed planar mapping of the flow in the water tunnel was completed near the region of cavitation inception. The effect of roughness on the downstream tip vortex was investigated. In this paper, these measurements are presented with discussion relative to the occurrence of cavitation.

Stock, M. J., Gharakhani, A. and Stone, C. P.

"MODELING ROTOR WAKES WITH A HYBRID OVERFLOW-VORTEX METHOD ON A GPU CLUSTER"

AIAA Paper 2010-4553, July 2010, Chicago, IL.

The vortex core shed from rotorcraft blades maintains coherency -- and thus dynamic relevance -- many blade turns after its creation. This presents a challenge to traditional Eulerian computational methods, as fine grids are required to suppress numerical diffusion which would weaken the vortex cores after a small number of revolutions. Vortex methods have been used in the past to overcome these problems, as they require computational elements only in vorticity-containing regions, but suffer from greater computational cost per element. In the present work, we will solve these problems with a hybrid Eulerian-Lagrangian method for modeling rotor wakes. An Eulerian OVERFLOW overset grid method computes the near-body flow, while a Lagrangian particle vortex method tracks the wake. The vortex method uses an anisotropic LES model to handle subgrid-scale dissipation explicitly. The computational cost of vortex methods is alleviated by using a parallel adaptive tree code on a cluster of machines each with multi-core CPU's and multiple cost-efficient graphics processing units (GPUs). Simulations of a low-Re sphere, finite wing, and 4-bladed rotor model are presented and are validated by comparisons with computational and experimental data.

Stoffers, G.

"WAKE VORTICES AND THEIR AERODYNAMIC ALLEVIATION: A REVIEW OF THE LITERATURE"

DFVLR-MITT-83-07, April 1983, DFVLR, Braunschweig, Germany

Wake vortex minimization and remedial measures to be taken at the vortex generating aircraft were investigated. Boeing 747, DC 10 and L 1011 aircraft were equipped with spoilers, winglets, ogee tips or splines, and flight tests, wind tunnel and water channel tests were performed. Best results are obtained with spoilers. It is concluded that the additional equipment gives rise to higher engine power delivery at ground approach/take off hence higher noise level and increased fuel consumption.

Stott, J. A. K. and Duck, P. W.

"EFFECTS OF VISCOSITY ON THE STABILITY OF A TRAILING-LINE VORTEX IN COMPRESSIBLE FLOW; FINAL REPORT"

NASA CR-194949, July 1994, Institute for Computer Applications in Science and Engineering, Hampton, VA

We consider the effects of viscosity on the inviscid stability of the Batchelor vortex in a compressible flow. The problem is tackled asymptotically, in the limit of large (streamwise and azimuthal) wavenumbers, together with large Mach numbers. Previous studies, with viscous effects neglected, found that the nature of the solution passes through different regimes as the Mach number increases, relative to the wavenumber. This structure persists when viscous effects are included in the analysis. In the present study the mode present in the incompressible case ceases to be unstable at high Mach numbers and a center mode forms, whose stability characteristics are determined primarily by conditions close to the vortex axis. We find generally that viscosity has a stabilizing influence on the flow, while in the case of center modes, viscous effects become important at much larger Reynolds numbers than for the first class of disturbance.

Stouff, C.

"LOOK AT INCIDENTS AND ACCIDENTS RECORDS AND LEARN TO IMPROVE PILOTS TRAINING"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 11-1 - 11-12.

While many people are doing some research on the wake vortex phenomenon to reduce the spacing minima because of the congestion now being experienced at major airports, accidents reports in France show that it would also be wise to look more thoroughly at general aviation and try to improve safety for pilots operating small aircraft under visual flight rules (VFR). Though the recent ICAO DOC 4444 which is now applied in France introduced increased spacing minima because of wake vortex, the procedures defined only apply to flights conducted under instrument flight rules (IFR). The situation is not crystal clear for light aircraft flying under VFR. Concerning the subject of wake vortices, the service that should be provided by Air Traffic Control is not clearly defined. For the past 3 years, 4 accidents and 1 incident caused by wake vortex have been reported to the French Accidents Investigations Office. In all cases, the aircraft was being operated under VFR for private purposes. As far as public transport is concerned, no accident was reported, only a few incidents which led to internal inquiries within the airline concerned. Not many incidents due to wake vortices are reported because, most of the time, the pilot does not identify clearly wake vortex as the cause, but often thinks it is due to some normal turbulence. This paper provides a comparative analysis of these accidents and incidents which occurred in France to small airplanes, and gives recommendations for improvements in the two fields concerned, Air Traffic Control and Pilots training.

Stough, III, H. P., Greene, G. C., Stewart, E. C., Stuever, R. A., Jordan, F. L., Rivers, R. A. and Vicroy, D. D.

"NASA WAKE VORTEX RESEARCH"

AIAA Paper No. 1993-4004, Monterey, CA, August 1993

NASA is conducting research that will enable safe improvements in the capacity of the nation's air transportation system. The wake-vortex hazard is a factor in establishing the minimum safe spacing between aircraft during landing and take-off operations and, thus, impacts airport capacity. The ability to accurately model the wake hazard and determine safe separation distances for a wide range of aircraft and operational scenarios may provide the basis for significant increases in airport capacity. Current and planned NASA research is described which is focused on increasing airport capacity by safely reducing wake-hazard-imposed aircraft separations through advances in several technologies including vortex motion and decay prediction, vortex encounter modeling, wake-vortex hazard characterization, and in-situ flow sensing.

Stowe, E. G.

"ANALOG PROCESSING ASSEMBLY FOR THE WAKE VORTEX LIDAR EXPERIMENT"

Langley Aerospace Research Summer Scholars, Part 2, January 1995, pp. 717-724

The Federal Aviation Administration (FAA) and NASA have initiated a joint study in the development of reliable means of tracking, detecting, measuring, and predicting trailing wake-vortices of commercial aircraft. Being sought is an accurate model of the wake-vortex hazard, sufficient to increase airport capacity by reducing minimum safe spacings between planes. Several means of measurement are being evaluated for application to wake-vortex detection and tracking, including Doppler RADAR (Radio Detection And Ranging) systems, 2-micron Doppler LIDAR (Light Detection And Ranging) systems, and SODAR (Sound Detection And Ranging) systems. Of specific interest there is the lidar system, which has demonstrated numerous valuable capabilities as a vortex sensor. Aerosols entrained in the vortex flow make the wake velocity signature visible to the lidar (the observable lidar signal is essentially a measurement of the line-of-sight velocity of the aerosols). Measurement of the occurrence of a wake vortex requires effective reception and monitoring of the beat signal which results from the frequency-offset between the transmitted pulse and the backscattered radiation. This paper discusses the mounting, analysis, troubleshooting, and possible use of an analog processing assembly designed for such an application.

Strain, J.

"FAST ADAPTIVE 2D VORTEX METHODS"

Journal of Computational Physics, Vol. 132, 1997, pp. 108-122

We present a new approach to vortex methods for the 2D Euler equations. We obtain long-time high-order accuracy at almost optimal cost by using three tools: fast adaptive quadrature rules, a free-Lagrangian formulation, and a useful new analysis of the consistency error. Our error analysis halves the order of differentiability required of the flow and suggests an efficient new balance of smoothing parameters which works well with fast summation schemes. Numerical experiments with our methods confirm our theoretical predictions and display excellent long-time accuracy.

Strangfeld, C., Nayeri, C. N., Paschereit, C. O. and Greenblatt, D.

"MECHANISM OF VORTEX PERTURBATION VIA UNSTEADY PITCHING"

Journal of Aircraft, Vol. 55, No. 5, September-October 2018, pp. 1831-1838.

Experiments indicate that vortices trailing finite wings can be perturbed by periodic wing pitching, leading to rapid dissipation and bursting. To illustrate the perturbation mechanism, Betz vortex rollup relations are combined with the Theodorsen theory for unsteady lift response. A sinusoidal pitch motion on a rigid elliptic planform wing is computed in this study as one example. Pitching modifies the instantaneous lift due to the planform variations, via the reduced frequency, and the rollup relations are applied to low-frequency experimental conditions. The combined Betz-Theodorsen theory shows that relatively large spanwise perturbations of the vortex centers can be achieved and may accelerate the exponential growth associated with the Crow instability. In fact, 84.2% of the displacement of the unsteady trailing vortices due to unsteady pitching is oriented in the direction of the Crow instability. Furthermore, the axial velocity in the vortex center, calculated based on the Batchelor method, varies on the order of the flight speed. This forms two types of stagnation points produced by approaching and retreating axial core velocities; in the former case, conservation of mass leads to observations of 'bursting.' This observation can be explained adequately on the basis of quasi-steady considerations.

Strasser, M. N.

"THE AERODYNAMIC AND DYNAMIC LOADING OF A SLENDER STRUCTURE BY AN IMPACTING TORNADO-LIKE VORTEX: THE INFLUENCE OF RELATIVE VORTEX-TO-STRUCTURE SIZE ON STRUCTURAL LOADING"

PhD Thesis, December 2015, University of Arkansas, Fayetteville, Arkansas.

Structural loading produced by an impacting vortex is a hazardous phenomenon that is encountered in numerous applications ranging from the destruction of residences by tornados to the chopping of tip vortices by rotors. Adequate design of structures to resist vortex-induced structural loading necessitates study of the phenomenon that control the structural loading produced by an impacting vortex. This body of work extends the current knowledge base of vortex-structure interaction by evaluating the influence of the relative vortex-to-structure size on the structural loading that the vortex produces. A computer model is utilized to directly simulate the two-dimensional impact of an impinging vortex with a slender, cylindrical structure. The vortex's tangential velocity profile (TVP) is defined by a normalization of the Vatistas analytical (TVP) which realistically replicates the documented spectrum of measured vortex TVPs. The impinging vortex's maximum tangential velocity is fixed, and the vortex's critical radius is incremented from one to one-hundred times the structure's diameter. When the impinging vortex is small, it interacts with vortices produced on the structure by the free stream, and maximum force coefficient amplitudes vary by more than 400 percent when the impinging vortex impacts the structure at different times. Maximum drag and lift force coefficient amplitudes reach asymptotic values as the impinging vortex's size increases that are respectively 94.77 percent and

10.66 percent less than maximum force coefficients produced by an equivalent maximum velocity free stream. The vortex produces maximum structural loading when its path is shifted above the structure's centerline, and maximum drag and lift force coefficients are respectively up to 4.80 percent and 34.07 percent greater than maximum force coefficients produced by an equivalent-velocity free stream. Finally, the dynamic load factor (DLF) concept is used to develop a generalized methodology to assess the dynamic amplification of a structure's response to vortex loading and to assess the dynamic loading threat that tornados pose. Typical civil and residential structures will not experience significant response amplification, but responses of very flexible structures may be amplified by up to 2.88 times.

Strasser, M. N. and Selvam, R. P.

"SELECTION OF A REALISTIC VISCOUS VORTEX TANGENTIAL VELOCITY PROFILE FOR COMPUTER SIMULATION OF VORTEX-STRUCTURE INTERACTION"

Journal of the Arkansas Academy of Science, Vol. 69, 2015, pp. 88-97.

Structure loading by vortices is a relevant phenomenon in numerous fields of engineering significance. Computer modelling is a powerful tool that can be used to study the loading produced on structures by impacting vortices. Realistic simulation of vortex-loading of structures necessitates the use of a realistic vortex tangential velocity profile (TVP). The present study compiles measured TVPs from various types of experimentally-produced vortices as well as real-world tornado and hurricane vortices. The measured TVPs are compared with commonly-used analytical TVPs. Analytical TVPs that realistically represent the range of measured TVPs are identified and selected for use in future computer simulation studies.

Strawn, R. C.

"OVERSET-GRID CFD MODELS FOR ROTORS AND WAKES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

Almost all of the aerodynamic design problems associated with rotorcraft involve interactions between the rotating blades and their aerodynamic wake systems. Prediction of the rotor wake is one of the most challenging problems in rotorcraft computational fluid dynamics (CFD). Typically, the computed vortical wakes diffuse too rapidly due to grid-related numerical dissipation. For general unsteady rotor flowfields, current numerical schemes and computational grids are unable to preserve the vortices long enough to accurately predict the noise and airloads caused by blade-vortex interactions (BVI's). This presentation describes results from steady-state Reynolds-averaged Navier-Stokes computations for hovering rotors and their vortex wake systems. The computations are designed to directly assess grid-related effects on the numerical results and employ: 1) structured overset-grids with high resolution on the rotor blades, 2) a systematic variation of grid resolution in the rotor wake, and 3) a systematic variation of outer boundary locations. The calculations show that the combination of high-order differencing schemes and fine computational meshes can provide rotor

blade performance predictions that are independent of both the rotor-wake grid size and the far-field boundary conditions. These performance predictions also show good agreement with experimental measurements for a four-bladed UH-60A model rotor in hover. The presentation will also assess the computational requirements for general unsteady forward-flight calculations with multiple blade-vortex interactions.

Strawn, R. C. and Ahmad, J. U.

"COMPUTATIONAL MODELING OF HOVERING ROTORS AND WAKES"

AIAA Paper No. 2000-0110, Reno, NV, January 2000

This paper presents a method for solving the Navier-Stokes equations for hovering rotors. This method runs efficiently on distributed memory parallel computers and uses a series of structured overset grids to model the near-body and off-body flowfields. The Navier-Stokes flow solver includes several enhancements for rotary-wing computations including steady-state rotational source terms, two-cell overlaps at overset grid boundaries, fourth-order spatial differencing, periodic and hovering-rotor far-field boundary conditions, and the development of a computationally-efficient system of off-body grids. Computed blade-loading results for two different grid densities in the rotor wake show good agreement with each other and also with experimental data from a UH-60 model rotor test.

Strawn, R. C. and Djomehri, M. J.

"COMPUTATIONAL MODELING OF HOVERING ROTOR AND WAKE AERODYNAMICS"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 786-793

Steady-state Reynolds-averaged Navier-Stokes computations are presented for a range of UH-60A model-rotor test cases in hover. The computations are designed to assess grid-related effects on the numerical results and employ 1) structured overset grids with high resolution on the rotor blades, 2) a systematic variation of grid resolution in the rotor wake, and 3) a systematic variation of outer-boundary locations. Computed rotor performance values agree very well with experimental measurements and show little sensitivity to either grid resolutions or outer-boundary locations. However, the computations uniformly overpredict the blade sectional thrust near the rotor tip. This overprediction of blade tip thrust is explained by an analysis of the circulation distribution in the computed rotor wake system.

Strawn, R. C., Kenwright, D. N. and Ahmad, J.

"COMPUTER VISUALIZATION OF VORTEX WAKE SYSTEMS"

AIAA Journal, Vol. 37, No. 4, April 1999, pp. 511-512

A new vortex detection scheme can identify vortex centers in overlapping regions of rotational flow, and it is easy to implement for structured-grid data sets. In addition to vortex identification, this

scheme can be used to guide adaptive-grid CFD methods that seek to locally improve the grid resolution for vortex wake systems. For rotorcraft applications, we expect that visualization tools such as this will become more and more important as solutions on larger computational grids begin to capture more of the fine details of the rotor blade-vortex interactions.

Streett, C. L.

"NUMERICAL SIMULATION OF FLUCTUATIONS LEADING TO NOISE IN A FLAP-EDGE FLOWFIELD"

AIAA Paper No. 1998-0628, Reno, NV, January 1998

In this paper we develop an approximate computational framework for simulation of the fluctuating flowfield associated with the complex vortex system seen at the side edge of a flap in a multi-element high-lift airfoil system. The eventual goal of these simulations is to provide an estimate of the spectral content of these fluctuations, in order that the spectrum of the noise generated by such flowfields may be estimated. Results from simulations utilizing this computational framework are shown.

Streit, T., Ronzheimer, A. and Buscher, A.

"NUMERICAL ANALYSIS OF TRANSPORT AIRCRAFT USING DIFFERENT WING TIP DEVICES"

Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 92, 2006, pp. 59-68.

Numerical solutions of the Navier Stokes equations for a modern transport configuration with three different wing tip devices are presented. Solutions are obtained at high speed for the cruise configuration and at low speed for the corresponding take-off configuration. This study is performed within the European Union project M-DAW (Modelling and Design of Advanced Wing Tip Devices). The numerical results are analyzed to characterize the performance of the wing tip devices using global force coefficients, local distributions of force and moment, surface contours and skin friction lines. In addition, the vortex wake was analyzed in the near field tip region for take-off. Numerical results are compared with experimental data obtained in cryogenic wind tunnel tests at high speed in the ETW (European Transonic Wind tunnel) and at low speed in the DNW-KKK (Cryogenic Wind Tunnel Cologne).

Stremel, P. M.

"A METHOD FOR MODELING FINITE-CORE VORTICES IN WAKE-FLOW CALCULATIONS"

AIAA Paper No. 1984-0417, Reno, NV, January 1984

A numerical method for computing nonplanar vortex wakes represented by finite-core vortices is presented. The approach solves for the velocity on an Eulerian grid, using standard finite-difference techniques; the vortex wake is tracked by Lagrangian methods. In this method, the distribution of continuous vorticity in the wake is replaced by a group of discrete vortices. An axially symmetric distribution of vorticity about the center of each discrete vortex is used to represent the finite-core model. Two distributions of vorticity, or core models, are investigated: a finite distribution of vorticity

represented by a third-order polynomial, and a continuous distribution of vorticity throughout the wake. The method provides for a vortex-core model that is insensitive to the mesh spacing. Results for a simplified case are presented. Computed results for the roll-up of a vortex wake generated by wings with different spanwise load distributions are presented; contour plots of the flow-field velocities are included; and comparisons are made of the computed flow-field velocities with experimentally measured velocities.

Struijs, R., Jonville, G., Darracq, D. and Heinrich, R.

"INVISCID COMPUTATION OF EFFECT OF WAKE VORTICES ON A SCALE-MODEL AIRPLANE"

Journal of Aircraft, Vol. 40, No. 1, January-February 2003, pp. 100-109

The forces and moments sustained by a scale-model airplane in the wake of another aircraft have been calculated using two different solvers. One solver uses a fourth-order central scheme with a specially adapted grid, whereas the other uses a chimera technique with second-order discretization. Additionally, simplified models were used on grids that are too coarse to represent vortices properly. These models work by handling the effect of the vortices by modifying the flux at the solid wall, or the fluxes in the domain. The experimental flowfield that contains wake vortices is modeled by a least-square fit analytical expression. This description is used as the inlet boundary condition for the Euler solvers. Numerical results agree with experiment and with previously published computations using panel methods.

Stuart, T. A., Mao, X. and Gan, L.

"TRANSIENT GROWTH ASSOCIATED WITH SECONDARY VORTICES IN GROUND/VORTEX INTERACTIONS"

AIAA Journal, Vol. 54, No. 6, June 2016, pp. 1901-1906.

The interaction of an isolated trailing vortex and the ground is investigated. An unsteady unperturbed flow is first calculated through a two-dimensional direct numerical simulation and then used as base flow for linear transient growth studies. The transient growth increases with Reynolds number and maximizes at streamwise wave number $3 \sim 5$ over the parameters considered. The most energetic initial perturbation is found to be located aside of the main vortex and convected by the base flow to the ground to interact with the separating boundary layer and the secondary vortex. Finally, the calculated perturbation is used to perturb the base flow in three-dimensional direct numerical simulation. It is observed that the secondary vortex and the rebound motion of the main vortex are both significantly suppressed. This observation indicates that the secondary structures are sensitive to external noise, and the widely reported secondary vortex and its induced rebound motion of the main vortex in two-dimensional direct numerical simulation would not appear or become much weaker in real conditions.

Stuber, K. and Gharib, M.

"EXPERIMENTS ON THE FORCED WAKE OF AN AIRFOIL"

AIAA Paper No. 1988-3840, Cincinnati, OH, July 1988

An experimental effort has been made to understand the nature of an airfoil wake whose oscillation frequency is controlled by the introduction of an external perturbation. The waves are introduced into the airfoil top and bottom surfaces' boundary layers by strip heaters; attention to the linear and nonlinear interactions of these wake waves has resulted in observation of three modes of interaction: (1) frequency locking, in which the vortex-shedding frequency is the same as the forcing frequency; (2) quasiperiodic vortex interaction, in which periodic clusters of vortices are observed in the wake; and (3) chaotic vortex interaction, in which the wake vortices exhibit a three-dimensional random structure.

Stuever, R. A. and Greene, G. C.

"AN ANALYSIS OF RELATIVE WAKE-VORTEX HAZARDS FOR TYPICAL TRANSPORT AIRCRAFT"

AIAA Paper No. 1994-0810, Reno, NV, January 1994

An analysis of relative wake-vortex hazards has been conducted for several typical transport configurations. The relative hazards associated with encountering aircraft wakes out of ground effect for various landing-spacing distances were assessed. The investigation was conducted to identify potential opportunities for safe reductions in wake-vortex landing-spacing distances, which can currently limit the operating capacity of major airports and create significant delays. The relative characteristics of the wakes of typical aircraft and their decay under various atmospheric conditions were first examined using a simple atmospheric vortex-decay model. A roll-axis, one-degree-of-freedom (1-DOF) representation of each aircraft was then employed to calculate relative wake upset hazards. A boundary of allowable vortex-induced bank angle versus altitude, established in a previous piloted-simulation investigation, served as the upset criteria. The effects of bank angle control and the geometry of vortex-pair linking were also studied to provide an additional measure of realism in the hazards assessment. Results suggest that there may be opportunities for reduced landing-spacing separations for certain aircraft pairs, especially under atmospheric conditions which promote rapid wake decay, and that the current U.S. landing-spacing weight-category boundaries may be too broad.

Stuever, R. A. and Stewart, E. C.

"THE ROLE OF SIMULATION IN DETERMINING SAFE AIRCRAFT LANDING SEPARATION CRITERIA"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 15-1 - 15-29

The role of flight simulation in determining safe aircraft landing separation criteria is reviewed and discussed. A broad conclusion is made that previous vortex-encounter simulations were useful for predicting the general response of an aircraft in the presence of trailing vortices and the type of separation criteria to emphasize. These simulations, however, were generally limited in scope and validation. Broad requirements for an accepted simulation methodology are presented. Key

technological issues are addressed, including the addition of high-fidelity vortex models and aircraft/vortex interaction effects in the simulation, and validation of simulations with experimental data. Finally, results from a preliminary one-degree-of-freedom simulation are shown. These indicate that reduced landing spacings may be feasible and that current aircraft categorizations should be reviewed.

Stuever, R. A., Stewart, E. C. and Rivers, R. A.

"OVERVIEW OF THE PREPARATION AND USE OF AN OV-10 AIRCRAFT FOR WAKE VORTEX HAZARDS FLIGHT EXPERIMENTS"

AIAA Paper No. 1995-3935, Los Angeles, CA, September 1995.

An overview is presented of the development, use, and current flight-test status of a highly-instrumented North American Rockwell OV-10A Bronco as a wake-vortex-hazards research aircraft. A description of the operational requirements and measurements criteria, the resulting instrumentation systems and aircraft modifications, system-calibration and research flights completed to date, and current flight status are included. The OV-10A performs several roles including meteorological-measurements platform, wake-decay quantifier, and trajectory-qualifier for wake encounters.

Stuff, R.

"THE RELATIONSHIP BETWEEN NEAR- AND-FAR-FIELD OF VORTEX WAKES FROM AIRCRAFT WITH HIGH ASPECT RATIO WINGS"

In New Results in Numerical and Experimental Fluid Mechanics III, Notes on Numerical Fluid Mechanics, Vol. 77, Eds. Wagner, et al., Springer-Verlag, Berlin Heidelberg, 2002, pp. 58-65.

Far field measurements of the vortex wake shed from a transport aircraft indicate that the trailing vortex pair from the main wing undergoes a Rayleigh-Ludwig instability and premature breakdown, if it encounters another vortex pair turning in the opposite sense. The origin of this latter vortex pair is the trim force of the horizontal tail, and, or, the reduction of lift across the fuselage due to the wing/fuselage junction. The opposite vortex pairs however, due to their self-induction, tend to move upwards whereas the main vortex pair moves downward. The condition, that the former does not happen is introduced as a necessary condition for premature vortex breakdown in the far field. This necessary condition can be checked upon in the near field. The Rayleigh-Ludwig instability then, is the sufficient condition for premature vortex breakdown.

Stuff, R.

"THE INVISCID MOTION OF A VORTEX PAIR IN A COMPRESSIBLE AND STRATIFIED ATMOSPHERE"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 31-1 to 31-10.

The movement of an inviscid vortex pair in a compressible atmosphere including buoyancy effects is described by analytic solutions. The effects of compressibility are dealt with in an isentropic atmosphere. The work of compression done by the atmosphere on the vortex is entirely consumed by the isentropic change of the thermodynamic state of the vortex pair. The acceleration of the accompanying and apparent mass is given by the displacement of the two vortices towards each other. The effects of buoyancy are investigated by means of a two-dimensional, incompressible, inviscid vortex pair which is heavier than the ambient fluid. It turns out that the condition of pressure continuity across the separating streamline can be achieved only by assuming an increase in circulation of the two vortices. The mass accompanying the vortex pair under the effect of non-conservative forces converts a fraction of its gravity potential into an increase of stagnation pressure. Both, the analytical formulas for compressibility and buoyancy, then, are combined to describe both effects simultaneously. Thus, inconsistencies of other papers are eliminated.

Stuff, R.

"ALLEVIATION OF AIRCRAFT VORTEX HAZARD THROUGH PASSIVE AERODYNAMIC MEASURES"

AIAA Paper No. 2003-1108, Reno, NV, January 2003

The hazard of wake vortices as encountered by following aircraft may be alleviated by a premature vortex breakdown because of the Rayleigh-Ludwig instability. Then, the rapidly increasing vortex cores soon meet at and merge across the wake center line. At this instant the circulation quickly decays, as the two vortex cores cancel each other due to their opposite vorticity. The Rayleigh-Ludwig instability, which is well known as an inviscid spiral instability occurring over delta wings, may also occur in the vortex wake shed from transport aircraft. The Rayleigh-Ludwig instability implies that the vorticity changes sign on each side of the wake. This may be accomplished by aerodynamic devices, or, modification of aerodynamic devices which, for other reasons than vortex breakdown, already are an integral part of the aircraft design. Thus, for example, the opposite vortex pair emanating in approach and climb from the horizontal tail may generate a premature vortex breakdown. On the one hand, the necessary condition is that the tail vortex pair is entrained into the descending wake of the main wing vortex pair and does not, due to its self-induction, move upward. On the other hand, the sufficient condition is that its circulation has a minimum value of about 20% of the wing vortex circulation. For alleviation of wake vortex hazard, the Rayleigh-Ludwig instability opens prospects for a novel category of passive aerodynamic measures, some of which are dealt with in the present paper.

Stuff, R.

"THE NEAR-FAR FIELD RELATIONSHIP OF VORTICES SHED FROM TRANSPORT AIRCRAFT"

AIAA Paper No. 2001-2429, Anaheim, CA, June 2001

A large amount of research effort has been devoted to the vortex breakdown of vortices caused by a Crow, Widnall or Crouch instability. In experiments dealt with here, a premature vortex breakdown in about 40 wingspans has been observed. The origin of this premature vortex breakdown is a counter-

rotating vortex emanating from inside flap edges or the horizontal tail. The origin of this instability is a counter-rotating vortex at the periphery of the wing vortex. In this case destabilizing centrifugal forces dominate restoring pressure forces. The instability was found by Rayleigh and generalized by Ludwig. A necessary condition for the occurrence of this instability is that the vortex pair emanating from the horizontal tail, due its self-induction, does not move upwards, whereas the main vortex pair moves downward. The necessary condition is used to establish the near-far field relationship. The instability of Rayleigh and Ludwig is the corresponding sufficient condition for premature breakdown of the vortex cores. Due to the rapid growth of the cores they become so large spatially that the two legs of the trailing main vortex pair meet and merge. After this merging the circulation rapidly decreases, which finally alleviates the hazard in encountering wake vortex.

Stuff, R.

"THE ROLE OF PIV IN THE DESIGN OF TRANSPORT AIRCRAFT FOR PREMATURE BREAKDOWN OF TRAILING VORTICES"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

The hazard of wake vortices as encountered by following aircraft is given by circulation and vortex spacing. The discrete vortices are rolled up from the vortex sheet shed from wide body aircraft, and the hazard may be greatly reduced if the two legs of the trailing wing vortex pair meet and merge already in the extended near field. This can be accomplished by premature breakdown of vortex cores due to the Rayleigh-Ludwig instability. After this breakdown the vortex cores grow so rapidly that they come across the wake center line and merge with the opposite vorticity emanating from the other side of the aircraft. Only after this merger a rapid decay of circulation can be expected. As the Rayleigh-Ludwig instability seems not to be well known in the English literature, a review of vortex breakdown and instabilities will be given. Using these findings, any aircraft may be characterized by a design point in the diagram, where the circulation ratio of wing and tail vortex is plotted over the corresponding spacing ratio. From this diagram, the necessary condition for premature breakdown according to Ludwig can be taken. The necessary condition implies that the self-induction of the tail vortex is superseded by the induction from the wing vortex pair, so that the tail vortex moves downward. The analytical stability criteria of Ludwig provides the sufficient condition for premature vortex breakdown. Whereas 2 Component Particle Image Velocimetry (2C-PIV) can be used for the necessary condition, 3 Component Particle Image Velocimetry (3C-PIV, Stereoscopic PIV) must be used for the sufficient condition, since the stability criteria of Ludwig is given by the radial gradients of the swirl and axial velocity components.

Stuff, R. and Vollmers, H.

"AIRCRAFT WITH MEANS FOR A PREMATURE BREAKDOWN OF THE WING VORTEX PAIR"

US Patent No. 6,422,518 B1, July 2002.

For a premature breakdown of a wing vortex pair behind an aircraft in flight comprising a symmetry plane, two wings, a fuselage and a horizontal tail plane, the wing vortex pair being generated in the area of the tips of the wings, having a first spin direction and descending behind the aircraft, an interfering vortex pair, which is generated between the fuselage and the tips of the wings without merging already in the near field behind the wing with the wing vortex pair and which has a second spin direction that is opposed to the first spin direction, is retained behind the aircraft in an altitude range of the wing vortices of the wing vortex pair by adjusting to suitable values the relative circulation and the relative span of the interfering vortex pairs each related to the wing vortex pair. The interfering vortex pair includes portions of a fuselage vortex pair, which is generated in the junction area of the wings to the fuselage, and a tail plane vortex pair, which is generated in the area of the wing tips of the horizontal tail plane.

Stuff, R., Dieterle, L., Horstmann, K-H., Pailhas, G., Coton, P. and Lozier, J.-F.

"NEAR- TO MIDFIELD-WAKE: EXPERIMENTAL CHARACTERISATION"

Proceedings 3rd ONERA-DLR Aerospace Symposium, Paris, France, June 2001, pp. S2-1/1-5

The wake of wide body aircraft is a hazard to following aircraft in approach, climb, and cruise. Thus, a large amount of experimental research effort has been devoted to instability and breakdown of vortices. However, investigations of the instabilities of vortices in the wake far field very often are lacking the link to the near field and are inconclusive as to the aerodynamic, whereas investigations of the wake in a wind tunnel very often miss the link to the mid- and far field at a sufficiently high Reynolds-number. For this reason, the wake of an Airbus A-300 with different flap settings was investigated in a joint ONERA/DLR-project in the catapult of ONERA Lille. The Particle Image Velocimetry was chosen as non-intrusive testing technique. In a particular setting of the landing flaps, a premature breakdown of the vortex cores was observed. The origin of the breakdown was understood as a Rayleigh-Ludwig instability, which occurs if destabilizing centrifugal forces dominate stabilizing pressure forces.

Stuhlpfarrer, M., Kummel, A. and Breitsamter, C.

"INVESTIGATIONS OF HELICOPTER WAKE FLOW INCLUDING ROTOR-HEAD MOTION"

Journal of Aircraft, Vol. 55, No. 5, September-October 2018, pp. 2114-2126.

The present paper emphasizes on the characteristics of the wake flowfield emanating from a helicopter fuselage and rotor head, including cyclic and collective pitch motion. Predicting the convection of the coherent vortical flow structures generated by the fuselage as well as the rotor head is a difficult goal by the application of numerical methods. Furthermore, the accurate determination of the wake flowfield requires the detailed knowledge of the origin of the associated coherent structures. Therefore, numerical and experimental investigations have been conducted on a twin-engine light utility helicopter. The wind-tunnel model includes a fuselage and a rotating five-bladed rotor head. To obtain the wake flowfield, stereoscopic particle image velocimetry is applied. The numerical

investigations are performed with a commercial flow solver. The flow solver is based on the unsteady Reynolds-averaged Navier-Stokes equations. Turbulence modeling is performed with the scale-adaptive simulation model. The motion of the rotor head is covered by the moving and deforming mesh methods. The wake-flow velocity distribution obtained by the experimental data and the numerical results shows a good agreement and allows a detailed analysis of the dominant vortical flow structures propagating downstream.

Stumpf, E.

"STUDY OF FOUR-VORTEX AIRCRAFT WAKES AND LAYOUT OF CORRESPONDING AIRCRAFT CONFIGURATIONS"

Journal of Aircraft, Vol. 42, No. 3, May-June 2005, pp. 722-730

A sequence of numerical simulations for the efficient determination of four-vortex wakes, consisting of two counter-rotating vortex pairs, with low induced rolling moments after the unstable merging of inner and outer vortices, is proposed. After a systematic investigation of generic four-vortex systems in a second step, an airliner geometry in high-lift configuration is modified such that it produces a vortex wake like the identified optimal four-vortex system. The configuration modification is done using simple design rules. For verification of the existence of a similar four-vortex system, the wake vortex of the modified airliner configuration is simulated up to the extended near field in a final step. Two four-vortex configurations are considered in the present paper, different only in the vortex spacing ratio. A maximum reduction of rolling moment down to 44-52% of the rolling moment of a reference two-vortex system is achieved within a distance equivalent to 2.89 n miles for a real size Airbus A340. The realization of four-vortex wakes behind an individually modified high-lift configuration like the aforementioned promising generic four-vortex configurations is demonstrated.

Stumpf, E.

"NUMERICAL INVESTIGATION OF THE EFFECT OF THE HIGH-LIFT CONFIGURATION OF A TRANSPORT AIRCRAFT ON ITS VORTEX WAKE"

In New Results in Numerical and Experimental Fluid Mechanics III, Notes on Numerical Fluid Mechanics, Vol. 77, Eds. Wagner, et al., Springer-Verlag, Berlin Heidelberg, 2002, pp. 50-57.

A numerical investigation, based on the Euler equations, of the nearfield wake vortex of four high-lift configurations of a narrow body airliner is carried out. The main focus is to study to what extent the configurations meet a criterion for the accelerated destruction of wake vortices proposed by Rennich/Lele. Additionally a spatial direct numerical simulation of the wake up to 35 spans is presented for the airliner model in standard landing configuration.

Stumpf, E.

"NUMERICAL STUDY OF FOUR-VORTEX AIRCRAFT WAKES AND LAYOUT OF CORRESPONDING HIGH-LIFT CONFIGURATIONS"

AIAA Paper No. 2004-1067, Reno, NV, January 2004

A numerical strategy for the efficient determination of 4-vortex wakes, consisting of two counter-rotating vortex pairs, with low induced rolling moments after the unstable merging of inner and outer vortices is proposed. After a systematic investigation of generic 4-vortex systems in a second step an airliner geometry in high-lift configuration is modified such that it produces a vortex wake like the identified optimal 4-vortex system. The configuration modification is done using simple design rules. For verification of the existence of a similar 4-vortex system the wake vortex of the modified airliner configuration is simulated up to the extended nearfield in a final step. Two 4-vortex configurations are considered in the present paper, different only in the vortex spacing ratio. A maximum reduction of rolling moment down to 44-52% of the rolling moment of a reference 2-vortex system is achieved within a distance equivalent to 2.89 NM for a real size Airbus A340. The realization of 4-vortex wakes behind an individually modified high-lift configuration like the afore determined promising generic 4-vortex configurations is demonstrated.

Stumpf, E.

"VORTEX WAKE OF AN A/C IN HIGH-LIFT CONFIGURATION"

XXV General Assembly, European Geophysical Society, Nice, France, April 2000

By means of Euler computations and Direct Numerical Simulations the vortex wake of a narrow-body wind-tunnel-model in different flight configurations has been investigated. The simulation domain covers in total 45 spans; aircraft configurations are landing, take-off and two configurations with differential flap setting. Special emphasis was put on the influence of atmospheric turbulence on the evolving wake. For the nearfield calculation up to half a span behind the model, the DLR-Euler code Tau was used; the downstream flowfield was simulated with the DLR-Direct Numerical Simulation code Mesoscop.

Stumpf, E.

"NUMERICAL STUDY OF FOUR-VORTEX AIRCRAFT WAKES"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

For an alleviation of wake vortices, it seems most promising to make use of the inherent instability of vortex systems: Either by triggering actively the most unstable wavelength with counteracting flaps and spoilers as proposed by Crow & Bate and patented by Boeing (Crouch & Spalart) or by designing a highly unstable vortex system for which natural perturbations from the aircraft boundary layer or weak atmospheric turbulence are sufficient for an onset of instability. For a four-vortex system, consisting of two pairs of counterrotating vortices, a point vortex analysis gives the condition for equal sink speed of all vortices in a cubic equation correlating the spacing ratio of the counterrotating vortices of the two

pairs with the ratio of their circulations. As the vortices lie constantly in one plane during decent, the outer vortex pair imposes high strain on the inner one, thereby in the first stage amplifying the inherent instabilities on the inner vortex pair. The second stage of the instability begins as the growing perturbation on the inner vortices induces instability on the outer vortex pair.

Stumpf, E., Hepperle, M., Darracq, D., Meese, E. A., Elphick, G. and Galpin, S.

"BENCHMARK TEST FOR EULER CALCULATIONS OF A HIGH LIFT CONFIGURATION VORTEX WAKE"

AIAA Paper No. 2002-0554, Reno, NV, January 2002

A benchmark test for Euler simulations of a high-lift configuration vortex wake is presented. Four different partners have used their in-house grid generators and Euler-codes within the framework of the European research program C-Wake for calculating the nearfield vortex wake of the DLR-F11 model in take-off configuration. Compared are nearfield results up to a half span downstream of the model wing tip obtained on structured and unstructured grids, employing second, third and fourth order accurate schemes. For validation 5-hole probe and pressure distribution measurements carried out in the DNW-NWB are used.

Stumpf, E., Rudnik, R. and Ronzheimer, A.

"EULER COMPUTATION OF THE NEARFIELD WAKE VORTEX OF AN AIRCRAFT IN TAKE-OFF CONFIGURATION"

Aerospace Science and Tech., Vol. 4, July 2000, pp. 535-543

Numerical simulations based on the three-dimensional Euler equations are used to investigate the predictive capability of an Euler code for calculations of the nearfield wake of a narrow-body airliner wind tunnel model in take-off configuration up to a half span behind the wing tip trailing edge. Simulation results on both structured and unstructured grids are presented. The results on the block-structured grid were obtained within the scope of the EU-project EUROWAKE. The simulation quality of the vortex formation and spatial development is analyzed by comparison to wind tunnel measurements of the spanwise lift distribution available from the EU-project DUPRIN II and to experimental PIV data available from the EU-project EUROWAKE.

Stumpf, E., Wild, J., Dafa'Alla, A. A. and Meese, E. A.

"NUMERICAL SIMULATIONS OF THE WAKE VORTEX NEAR FIELD OF HIGH-LIFT CONFIGURATIONS"

European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS 2004, Jyväskylä, Finland, July 2004

Euler simulations of the nearfield wake of the DLR-F11 model in take-off configuration and a very large transport model in landing configuration are performed using the DLR TAU code on unstructured grids. The aim of the investigation is firstly to analyze the predictive capability of an Euler code for

high-lift configuration vortex wakes and secondly to study configuration effects on the vortex wake nearfield. A grid adaption strategy and parameter settings for the flow simulation are determined by validation with 5-hole probe measurement results that lead to good agreement between simulation and experiment at a half wing span downstream of the model wing tip. The identical simulation procedure is applied to a very large transport aircraft configuration and the interaction between the outer region jet and the flap side-edge vortex is investigated.

Sturdy, J. L.

"WAKE TURBULENCE MITIGATION FOR DEPARTURES (WTMD) PROTOTYPE SYSTEM"

NASA/CR-2008-215549, January 2008, Raytheon Co., Hampton, VA.

This document describes the software design of a prototype Wake Turbulence Mitigation for Departures (WTMD) system that was evaluated in shadow mode operation at the Saint Louis (KSTL) and Houston (KIAH) airports. This document describes the software that provides the system framework, communications, user displays, and hosts the Wind Forecasting Algorithm (WFA) software developed by the MIT Lincoln Laboratory. The WFA algorithms and software are described in a separate document produced by Lincoln Laboratory.

Sturgeon, M. C.

"WIND TUNNEL TESTS OF SOME LOW-COST SONIC ANEMOMETERS"

WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation, May 2005, Bucharest, Romania.

Sonic anemometers for meteorological measurements have been around since the early 1970s. The early sonic anemometers were very expensive and did not have the high reliability, low-cost electronic components now available. Thus, early sonic anemometers had poor reliability and were mainly used for scientific research. In the last several years, manufacturers have started offering lower-cost sonic anemometers suitable for general meteorological use. The low maintenance and low electrical power requirements of these current sonic anemometers make them good candidates for remote sensing applications with solar panels. This paper presents test data for several available low-cost sonic anemometers using wind tunnel test method ISO 16622 'Meteorology -- Sonic anemometers/thermometers - Acceptance test methods for mean wind measurements.' The measurement performance differences of sonic anemometers and rotating anemometers are discussed in this paper.

Subaschandar, N. and Prabhu, A.

"TURBULENT NEAR-WAKE STUDIES BEHIND AN INFINITELY SWEPT WING"

Journal of Aircraft, Vol. 39, No. 2, March-April 2002, pp. 290-295.

The three-dimensional asymmetric turbulent near-wake behind an infinitely swept wing with GAW(2) airfoil has been investigated at low speeds. The near-wake in the present study is asymmetric because the boundary layers on the top and bottom surfaces of the model develop under different streamwise pressure gradients. Distributions of mean velocity, three turbulent normal stresses, and two important Reynolds shear stresses have been measured using hot-wire anemometry. The profiles of mean velocity and Reynolds shear stresses exhibit asymmetry near the trailing edge and seem to have become symmetric within a short distance of 60 trailing edge momentum thicknesses. Results of computation using K- ϵ turbulence model with a simple scheme to predict the near-wake behind the swept wing have also been presented and compared with the experimental data. The agreement of the predicted mean flow development with the experiment is fair considering the simplicity of the scheme.

Suciu, E. O.

"A FINITE ELEMENT ANALYSIS OF THE EXACT NONLINEAR FORMULATION OF A LIFTING SURFACE IN STEADY INCOMPRESSIBLE FLOW, WITH THE EVALUATION OF THE CORRECT WAKE GEOMETRY"

M.S. Thesis, December 1975, Boston University, Boston, MA

The problem of steady incompressible flow around wings with wake roll-up is considered. This problem requires the solution of an integral equation relating the values of the potential on the lifting surface and its wakes to the values of the normal derivative of the potential which are known from the boundary conditions. An iteration procedure is used to obtain the wake geometry; the velocities at the corner points of the wake elements are calculated and the (originally straight) wake streamlines are aligned to be parallel to the velocity vector. The procedure is repeated until convergence is attained.

Suciu, E. O. and Morino, L.

"NONLINEAR STEADY INCOMPRESSIBLE LIFTING-SURFACE ANALYSIS WITH WAKE ROLL-UP"

AIAA Journal, Vol. 15, No. 1, January 1977, pp. 54-58.

The problem of lifting surfaces in steady incompressible flow is considered. The problem is formulated in terms of an integral equation relating the potential discontinuity on wing and wake to the normal derivative of the potential (normal wash) on the lifting surface. The integral equation is approximated by a system of linear algebraic equations obtained by dividing the surfaces into small quadrilateral elements and by assuming the potential discontinuity and the normal wash to be constant within each element. The wake geometry is obtained through iteration by satisfying the condition that the velocity be tangent to the surface of the wake and that the discontinuity be constant along the streamlines. Numerical results are in good agreement with existing ones.

Sudakov, V. G. and Sychev, V. V.

"ASYMPTOTIC THEORY OF THE VISCOUS INTERACTION BETWEEN A VORTEX AND A PLANE"

Fluid Dynamics, Vol. 37, No. 6, 2002, pp. 865-872

The problem of the viscous interaction between a flow induced by a vortex filament and an orthogonal rigid surface is solved for high Reynolds numbers using the method of matched asymptotic expansions. In view of the impossibility of matching the principal terms of the asymptotic expansions directly for the near-axial boundary layer and the main flow zone, the solution is obtained by introducing two intermediate zones. In this case a logarithmic singularity of the axial velocity arises inevitably on the vortex filament. In the near-axial and intermediate zones the solution is obtained numerically and analytically, respectively, while in the main zone the problem reduces to the problem of the flow induced by a line of weakly swirled vortex-sinks.

Sugimoto, T.

"INDUCED VELOCITY IN THE PLANE OF AN ELLIPTICALLY LOADED LIFTING LINE"

AIAA Journal, Vol. 40, No. 6, June 2002, pp. 1233-1236

The classical lifting line theory of Prandtl is first reviewed. Then with special attention to the treatment of singularities at the vortex sheet edges, the lifting line theory was utilized to obtain the distribution of induced velocity in the plane of an elliptically loaded lifting line and its wake. The resulting closed form solution, although simplistic in physical terms, may serve as a benchmark test for validating numerical schemes.

Sugiura, M. and Matayoshi, N.

"ACCURACY ESTIMATION OF PROBABILISTIC WAKE VORTEX PREDICTION CONSIDERING WEATHER INFORMATION ERRORS"

AIAA Paper No. 2011-3195, June 2011, Honolulu, Hawaii.

Current wake vortex separation minima are a major impediment to increasing traffic capacity since they require greater separation than radar separation minima. The concept of dynamic wake vortex separation minima, which would allow reduced separations in favorable meteorological conditions when wake durations on flight paths become shorter, would allow an increase in capacity. This paper proposes a methodology that uses a probabilistic wake vortex prediction model to probabilistically assure that wake vortex encounter risk at reduced separations are equal or lower than the risks at current separations.

Sugiura, M., Tanabe, Y., Sugawara, H., Matayoshi, N. and Ishii, H.

"NUMERICAL SIMULATIONS AND MEASUREMENTS OF THE HELICOPTER WAKE IN GROUND EFFECT"

Journal of Aircraft, Vol. 54, No. 1, January-February 2017, pp. 209-219.

When a helicopter takes off, lands, or makes hovering or taxiing flights in ground effect, its downwash interferes with the ground. Encounters with such highly turbulent helicopter wakes have resulted in the two small fixed-wing aircraft crashes in the United Kingdom. Due to these accidents, the Japan Aerospace Exploration Agency is investigating the helicopter wake structure in ground effect, especially during taxiing, by means of computational fluid dynamics and flight testing. The base computational fluid dynamics code is structured grid solver rFlow3D, which has systematically been developed for helicopter applications at the Japan Aerospace Exploration Agency. The rFlow3D solver is a highly versatile computational fluid dynamics code that can numerically simulate flows around helicopters with a wide range of Reynolds and Mach numbers and can perform rotor trim analysis with elastic blade deformations. In the flight experiment described herein, the Japan Aerospace Exploration Agency research helicopter H145 (EC145, BK117 C-2) performed taxiing above a runway, and its wakes were measured by Light Detection and Ranging and ultrasonic anemometers. The variation of the characteristic wake structure with the advance ratio was clearly revealed in the computational fluid dynamics and was supported indirectly by the flight experiment results.

Sullivan, I. S., Niemela, J. J., Hershberger, R. E., Bolster, D. and Donnelly, R. J.

"DYNAMICS OF THIN VORTEX RINGS"

J. Fluid Mech., Vol. 609, 2008, pp. 319-347

As part of a long-range study of vortex rings, their dynamics, interactions with boundaries and with each other, we present the results of experiments on thin core rings generated by a piston gun in water. We characterize the dynamics of these rings by means of the traditional equations for such rings in an inviscid fluid suitably modifying them to be applicable to a viscous fluid. We develop expressions for the radius, core size, circulation, and bubble dimensions of these rings. We report the direct measurements of the impulse of a vortex ring by means of a physical pendulum.

Sullivan, J. P., Widnall, S. E. and Ezekiel, S.

"A STUDY OF VORTEX RINGS USING A LASER DOPPLER VELOCIMETER"

AIAA Paper No. 1973-0105, Washington, DC, January 1973

Measurements of the axial and radial velocity distributions in vortex rings were made using a two-component laser Doppler velocimeter. The rings were generated by pulsing air through a sharp-edged orifice using a loudspeaker: the strength and vortex core size could be controlled somewhat by the duration and amplitude of the pulse. From detailed surveys of the velocity field, both the circulation and vorticity distribution were found for two different rings: one with a relatively thick core, the other with a thin core. The vorticity was found to be rather concentrated for both rings. Streamlines were also calculated and compared with observations. Vortex rings were found to be unstable to azimuthal perturbations; the observed mode number and growth rate are in reasonable agreement with theory.

Sullivan, R. D.

"A PROGRAM TO COMPUTE THE BEHAVIOR OF A THREE-DIMENSIONAL TURBULENT VORTEX"

ARL-TR-74-009 and ARAP No. 200, February 1974, Aeronautical Research Assoc. of Princeton, Princeton, NJ

A program to compute the downstream behavior of a turbulent vortex has been prepared for Aerospace Research Laboratories. The mathematical basis and the numerical technique of the program are set forth. Subsidiary calculations are described. Finally, the structure of the program is explained and information needed to run it is given.

Sullivan, T. E. and Burnham, D. C.

"GROUND-WIND VORTEX SENSING SYSTEM CALIBRATION TESTS"

FAA-RD-80-13, February 1980, DOT Transportation Systems Center, Cambridge, MA

This report describes the collection of data related to the calibration of two systems for detecting and tracking aircraft wake vortices. The systems tested were the propeller anemometer Ground Wind Vortex Sensing System and the Pulsed Acoustic Vortex Sensing System. The data were analyzed and the location of the vortices as determined with these systems were compared with the vortex location as determined photographically.

Sullivan, T. E., Burnham, D. C. and Kodis, R. D.

"VORTEX SENSING TESTS AT LOGAN AND KENNEDY AIRPORTS"

FAA-RD-72-141, December 1972, DOT Transportation Systems Center, Cambridge, MA

This report describes a series of tests of wake vortex sensing systems at Logan and Kennedy Airports. Two systems, a pulsed acoustic radar (ACDAR) and an array of ground level pressure sensors, were tested. Site restrictions limited the Logan work to preliminary evaluation. The tests at Kennedy Airport established the general operating characteristics of both tracking systems. It was found that the acoustic sensor can detect and track the vortices of all commonly used commercial aircraft, though with varying degrees of sensitivity. The pressure sensors generally behaved best during conditions of low to moderate winds when the vortices could often be tracked laterally up to several hundred feet from the aircraft flight path.

Sullivan, T. E., Hallock, J. N. and Winston, B. P.

"ANALYSIS OF GROUND-WIND VORTEX SENSING SYSTEM DATA FROM O'HARE INTERNATIONAL AIRPORT"

FAA-RD-80-133, September 1980, DOT Transportation Systems Center, Cambridge, MA

From July 1976 through September 1977, aircraft wake vortex data were collected on the approach to runways 14R, 27R, and 32L at O'Hare International Airport. The vortices from over 21,000 aircraft were tracked using the propeller anemometer Ground-Wind Vortex Sensing System, and the vortex behavior as correlated with the associated ambient meteorological conditions. The primary purpose of the tests was the evaluation of the Vortex Advisory System (VAS) concept. The elliptical wind criterion used in the VAS was verified using the vortex data.

Sullivan, T. E., Hallock, J. N., Winston, B. P., McWilliams, I. G. and Burnham, D. C.

"AIRCRAFT WAKE VORTEX TAKEOFF TESTS AT TORONTO INTERNATIONAL AIRPORT"

FAA-RD-78-143, February 1979, DOT Transportation Systems Center, Cambridge, MA.

This report describes the collection and analysis of data related to the behavior of the wake vortices of departing aircraft. The test site was located on the departure end of Runway 23L at Toronto International Airport, Toronto, Ontario, Canada. Three arrays of Ground Wind Vortex Sensing Systems and one Monostotic Acoustic Vortex Sensing System were used to detect, track and measure the strength of the vortices. The data were analyzed to determine vortex lifetimes, transport characteristics and decay mechanism. The results of the data analysis were used to generate an elliptical wind rose criterion like that used in the Vortex Advisory System for reduction in interarrival aircraft spacings.

Sun, D., Wu, H., Lam, C. M. and Zhu, R.

"DEVELOPMENT OF A SMALL AIR VEHICLE BASED ON AERODYNAMIC MODEL ANALYSIS IN THE TUNNEL TESTS"

Mechatronics, Vol. 16, Issue 1, February 2006, pp. 41-49

Tunnel tests play a critical role to aerodynamics analysis, but few work has been done in this area for developing small air vehicles. This paper presents development of an electrically powered small air vehicle prototype based on aerodynamic analysis in wind tunnel and water tunnel tests. Firstly, two airframe models in triangle and square wing planforms, each with a wingspan of 100 mm, are analyzed with a small-scale low speed wind tunnel. The purpose of the wind tunnel test is to examine the practical characteristics such as lift and drag coefficients. The test in a water tunnel is further carried out to investigate the relationship between the vortex airfoil design and turbulences created. In both wind tunnel and water tunnel tests, the airframe models, apparatus, and the methodology are discussed, and the testing results show that the triangle wing airfoil appears greater maximum lift coefficient and little occurrence of vortex and turbulences. Secondly, based on the verified wing planform in the tunnel tests, a small air vehicle prototype was designed and fabricated. The ground and onboard subsystems or components, such as flight control unit, vision system, and propulsion system etc., are studied. The materials and fabrication processes are also presented in the paper. Finally, the developed air vehicle prototype is successfully tested in the real flight.

Sun, G. and Qiao, Z.

"AN ADAPTIVE REGION METHOD FOR COMPUTATION OF VORTEX SHEET BEHIND WING IN COMPRESSIBLE FLOW"

ICAS 1992, Paper No. 7.4.1, September 1992, Beijing, China.

An adaptive region method is presented for the computation of vortex sheet behind wing in compressible flow, by adjusting automatically computation region in size on every Trefftz plane. The method can keep the boundary of computation region sufficiently away from the region of vorticity to ensure the accuracy with less computation time. In addition, the first derivatives of the potential on branch cuts is redefined and a second derivative of potential function is obtained for improving calculation of the cross velocity on branch cuts. Computation shows that the 'hook' at vortex tip which appeared by using Stremeland, Murman's method for elliptically loaded wing, is eliminated in the present method and the computation results are quite agreement with exact solution of Betz theory for elliptically loaded wing.

Sun, J., Vu, H., Ellerbrook, J. and Hoekstra, J. M.

"WEATHER FIELD RECONSTRUCTION USING AIRCRAFT SURVEILLANCE DATA AND A NOVEL METEO-PARTICLE MODEL"

PLoS ONE, Vol. 13, Issue 10, October 2018, pp. e0205029-1 to e0205029-33.

Wind and temperature data are important parameters in aircraft performance studies. The lack of accurate measurements of these parameters forces researchers to rely on numerical weather prediction models, which are often filtered for a larger area with decreased local accuracy. Aircraft, however, also transmit information related to weather conditions, in response to interrogation by air traffic controller surveillance radars. Although not intended for this purpose, aircraft surveillance data contains information that can be used for weather models. This paper presents a method that can be used to reconstruct a weather field from surveillance data that can be received with a simple 1090 MHz receiver. Throughout the paper, we answer two main research questions: how to accurately infer wind and temperature from aircraft surveillance data, and how to reconstruct a real-time weather grid efficiently. We consider aircraft as moving sensors that measure wind and temperature conditions indirectly at different locations and flight levels. To address the first question, aircraft barometric altitude, ground velocity, and airspeed are decoded from down-linked surveillance data. Then, temperature and wind observations are computed based on aeronautical speed conversion equations. To address the second question, we propose a novel Meteo-Particle (MP) model for constructing the wind and temperature fields. Short-term local prediction is also possible by employing a predictor layer. Using an unseen observation test dataset, we are able to validate that the mean absolute errors of inferred wind and temperature using MP model are 67% and 26% less than using the interpolated model based on GFS reanalysis data.

Sun, M. and Curtiss, Jr., H. C.

"ROTOR VORTEX WAKE DISTORTION AND ITS INDUCED VELOCITY IN GROUND EFFECT AT LOW SPEED"

Acta Aerodynamica Sinica, Vol. 7, March 1989, pp. 35-41

The vortex wake and its induced velocity of a helicopter rotor operating near the ground at low forward speeds have been studied using a simplified free wake-ground vortex model. The vortex wake near the rotor plane is distorted significantly because of the flowfield of the ground and ground vortex, resulting in large variation on the induced velocity distribution at the rotor plane, especially near the rotor leading edge. The variation of the induced velocity distribution at the rotor plane caused by the ground and ground vortex through distorting the rotor near-wake is much larger than that induced directly by the ground and ground vortex. The free wake-ground vortex model can be used to predict the induced velocity distribution at the rotor plane with reasonable accuracy.

Sun, M. and Marshall, J. S.

"A FLOW VISUALIZATION STUDY OF VORTEX INTERACTION WITH THE WAKE OF A SPHERE"

Transactions of the ASME, Vol. 122, September 2000, pp. 560-568

A study of the interaction between an initially columnar intake vortex (hereinafter referred to as the primary vortex) and vortex structures in the wake of a single sphere (hereinafter referred to as secondary vortices) is performed using a series of flow visualization experiments, in which a sphere is towed toward a stationary vortex with ambient axial flow and gradually decelerated to rest at a specified distance from the vortex core axis. Both the primary vortex core and the boundary layer of the sphere are visualized using laser-induced fluorescent dyes of two different colors, which are illuminated either with a laser sheet or a laser volume. The strength of the primary vortex is measured using particle-image velocimetry, which is also used to measure the strength of the secondary vortices in select cases. The form of the sphere wake in the presence of the primary vortex and the effect of the induced velocity from the secondary vortices on the primary vortex are studied for different values of the vortex-sphere separation distance, the sphere diameter, and the primary vortex core radius. Weak secondary vortices are observed to induce formation of small-amplitude waves of varying core area on the primary vortex, eventually forming a turbulent sheath surrounding the primary vortex. Stronger secondary vortices have an increasingly strong effect on the primary vortex, including large-amplitude variation in core area, outward ejection of fluid from the primary vortex core, and breakdown of the primary vortex.

Sun, Y. and Smith, H.

"REVIEW AND PROSPECT OF SUPERSONIC BUSINESS JET DESIGN"

Progress in Aerospace Sciences, Vol. 90, 2017, pp. 12-38.

This paper reviews the environmental issues and challenges appropriate to the design of supersonic business jets (SSBJs). There has been a renewed, worldwide interest in developing an environmentally friendly, economically viable and technologically feasible supersonic transport aircraft. A historical

overview indicates that the SSBJ will be the pioneer for the next generation of supersonic airliners. As a high-end product itself, the SSBJ will likely take a market share in the future. The mission profile appropriate to this vehicle is explored considering the rigorous environmental constraints. Mitigation of the sonic boom and improvements aerodynamic efficiency in flight are the most challenging features of civil supersonic transport. Technical issues and challenges associated with this type of aircraft are identified, and methodologies for the SSBJ design are discussed. Due to the tightly coupled issues, a multidisciplinary design, analysis and optimization environment is regarded as the essential approach to the creation of a low-boom low-drag supersonic aircraft. Industrial and academic organizations have an interest in this type of vehicle are presented. Their investments in SSBJ design will hopefully get civil supersonic transport back soon.

Sun, Z., Li, Q. and Bruecker, C.

"THE SHORT-WAVELENGTH INSTABILITY IN THE IMPINGING VORTEX RING MEASURED BY SCANNING-PIV"

19th International Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics, July 2018, Lisbon, Portugal.

Scanning-PIV using the drum scanner is employed to study the impingement of a vortex ring onto a solid surface. Both the wall-normal and wall-parallel planes are measured. The former reveals the expansion of the vortex ring and the generation of the secondary and even the tertiary rings in the impingement. The latter successfully visualized the development of the azimuthal instability in the primary and secondary rings. The well-understood long-wavelength instability is found to occur when the secondary ring moves into the primary one. Apart from the azimuthal instability of long-wavelength, another azimuthal instability phenomenon of short-wavelength is visualized. This short-wavelength instability along the primary ring happens when it approaches the surface and being stretched.

Suponitsky, V., Cohen, J. and Bar-Yoseph, P. Z.

"NUMERICAL INVESTIGATION OF THE EVOLUTION OF A LOCALIZED VORTEX DISTURBANCE IN UNIFORM SHEAR FLOW"

AIAA Paper No. 2003-3603, Orlando, FL, June 2003

The motivation of the present research is to understand the generation of coherent structures in turbulent boundary layers from a localized finite amplitude vortical disturbances. Our basic methodology is to follow the evolution of a localized vortical disturbance in an unbounded laminar uniform shear flow instead of a turbulent environment. Here we focus only on the interaction between the shear of the base flow and the disturbance and do not consider other effects such as the presence of a wall or the non-uniformity of the shear of the base flow. The numerical simulation are performed by the commercial CFD code ('FLUENT') based on the infinite volume approach. For the case of a small amplitude initial Gaussian vortex the numerical solution of the full Navier-Stokes equations follows

closely the analytical solution of the linearized equations. When the amplitude of the disturbance is small, the disturbance evolves into a pair of quasi-streamwise counter-rotating elongated vortices, similar to the ones observed in the near-wall region of a turbulent boundary layer independent of the initial disturbance geometry. On the other hand, when the amplitude of the initial disturbance is large the initial disturbance eventually evolves into a hairpin shape vortex. During its evolution the strength of the vortical structure as well as its inclination angle relative to the direction of the base flow, strongly depend on the initial geometrical shape of the small amplitude initial disturbance, although the resulted structures are very similar.

Surendraiah, M.

"AN EXPERIMENTAL STUDY OF ROTOR BLADE VORTEX INTERACTION"

NASA CR-1573, December 1969, Penn State University, Dept. Aerospace Engineering, University Park, PA

Results of an experimental investigation of the instantaneous blade airloads and their time derivatives are presented for a rotor blade intersecting a completely rolled-up trailing vortex. Parameters such as the rotor rotations per minute, vortex strength, and intersection angle were examined. Sample photographic records are presented in order to show the influence of the tip vortex on the blade loading.

Surmacz, K. and Lotnictwa, I.

"DYNAMICS OF A VORTEX RING AROUND A MAIN ROTOR HELICOPTER"

ICAS 2014, September 2014, St. Petersburg, Russia.

The main goal of the work was an analysis of the dynamics of vortex ring formation process and determinants of the occurrence of vortex ring state (VRS) in a main rotor of a helicopter. VRS occurs in the vertical decent of a helicopter (or close to this maneuver). The paper presents results obtained by CFD analysis and from the wind tunnel test investigation. The visualization of a flow field provided information on the changing nature of the flow during the movement of helicopter.

Sussmann, R.

"VERTICAL DISPERSION OF AN AIRCRAFT WAKE: AEROSOL-LIDAR ANALYSIS OF ENTRAINMENT AND DETRAINMENT IN THE VORTEX REGIME"

Journal of Geophysical Research, Vol. 104, No. D2, January 1999, pp. 2117-2129

Vertical dispersion of contrails in the vortex regime is investigated by focusing on the role of entrainment and detrainment of exhaust with respect to the pair of trailing vortices. A ground-based back-scatter-depolarization lidar with an integrated CCD camera provides information on optical and geometrical parameters of the contrail in the time span between 5.7 and 50.3 s behind a B747-400

aircraft. This is combined with coincident airborne in situ measurements of turbulence and the vertical profiles of temperature and wind speed in a case study. The two wingtip vortices, separated by 47 m, are descending with an increasing speed (2.5-3.1 m/s for 10.8-47.8 s behind aircraft) in the weakly non-stably stratified atmosphere. The turbulent vertical dissipation rate on the day of the study above southern Germany is a factor of 1000 higher than found typically above oceans at cruising altitude. At 4.2 s behind the aircraft, a diffuse secondary wake starts to evolve above the two wingtip vortices. After about 50 s the secondary wake encloses a cross-sectional area (4410 square m) comparable to that of the primary wake (4620 square m) and a relative ice surface area of 1:5. The observed early onset of the secondary wake is conjectured to be due to turbulent detrainment of fluid out of the primary wake which can be enhanced by detrainment due to baroclinic forces later in the vortex regime evolution. By exclusion of other mechanisms of secondary wake formation, detrainment of fluid from the primary wake is concluded to be the precondition for secondary wake formation. Detrainment due to baroclinic forces, shear or turbulence is, in general, unlikely to be absent for typical atmospheric conditions. It is suggested that the ambient humidity level may determine when a secondary wake is visible above a vortex pair and when it is not.

Sussmann, R. and Gierens, K. M.

"LIDAR AND NUMERICAL STUDIES ON THE DIFFERENT EVOLUTION OF VORTEX PAIR AND SECONDARY WAKE IN YOUNG CONTRAILS"

Journal of Geophysical Research, Vol. 104, No. D2, January 1999, pp. 2131-2142.

Vortex-regime evolution of contrails is investigated by focusing on the role of ambient humidity. Lidar cross-section measurements and observational analysis are combined with numerical simulations of fluid dynamics and microphysics. Contrail evolution behind four-turbofan aircraft is classified into three different scenarios. In the case of ice-subsaturated air, a visible pair of wingtip vortices is formed that disappears at the end of the vortex regime. In case of ice supersaturation, a diffuse secondary wake evolves above the wingtip vortices. It is due to detrainment of ice particles growing by sublimation of ambient humidity. A vertical wake-gap opens between the wingtip vortices and the secondary wake. It is due to subsaturated air moving upward along the outer edges of the sinking vortex tubes accumulating around the upper stagnation point of the vortex system. The vertical wake-gap preferably occurs in the wake of heavy (four turbofans) aircraft, since the vortices behind light aircraft migrate down too slowly. The secondary wake is composed of nonspherical particles larger than the ones in the wingtip vortices which are spherical particles and/or particles smaller than about 0.5 microns. In most cases the secondary wake is the only part of a contrail that persists after vortex breakdown. This is because the ice in the vortex tubes evaporates due to adiabatic heating as the vortices travel downward. Only in the rare case of higher ambient ice supersaturation (greater than 2 percent) do both parts of a contrail contribute to the persistent ice cloud.

Sussmann, R. and Gierens, K. M.

"DIFFERENCES IN EARLY CONTRAIL EVOLUTION OF TWO-ENGINE VERSUS FOUR-ENGINE AIRCRAFT: LIDAR MEASUREMENTS AND NUMERICAL SIMULATIONS"

Journal of Geophysical Research, Vol. 106, No. D5, March 2001, pp. 4899-4911.

Jet- and vortex-regime evolution of contrails behind cruising aircraft is investigated by focusing on the role of aircraft type. Cross-section measurements by ground-based lidar and observational analysis are combined with numerical simulations of fluid dynamics and microphysics in the wake of a two-engine aircraft. Depending on ambient humidity levels, contrail evolution behind short-/medium-range twin-turboprop airliners is classified into two scenarios, which contrasts with the three scenarios observed for a wide-body four-turboprop aircraft. In the case of ice-subsaturated ambient air, a short visible contrail is formed behind a two-engine aircraft that disappears before the ice is fully entrained into the wingtip vortices (in most cases about 4 s behind aircraft). The early evaporation of the ice is mainly due to the fast initial jet expansion, mixing the exhaust with the ambient air. Contrails behind a wide-body four-engine aircraft always survive at least until vortex breakdown (i.e., typically 2 min behind aircraft). This is simply due to the larger ice mass in the contrail because of the higher fuel flow rate. Generally, in the case of ice supersaturation, a diffuse secondary wake evolves above the primary vortex wake. For a two-engine aircraft, always the whole contrail persists, while for a four-engine aircraft, the ice inside the primary wake disappears in most cases after vortex breakdown, when the relative humidity is only slightly above ice saturation. In the more rare cases of higher ice-supersaturation the ice in the primary wake survives vortex breakdown and becomes part of the persistent contrail.

Sussmann, R. and Jager, H.

"VORTEX DYNAMICS BEHIND CRUISING AIRCRAFT STUDIED BY A GROUND-BASED SCANNING LIDAR AND AIRBORNE IN SITU MEASUREMENTS"

Proceedings SPIE, Vol. 3104, Lidar Atmospheric Monitoring, May 1997, pp. 212-223.

By LIDAR and CCD camera analysis the geometrical evolution of a vortex phase contrail (descent rate 2.7 m/s, vortex separation 47 m, vertical extension 140 m after 77 s) is analyzed. The contrail of a four-engine aircraft is showing a diffuse central wake phenomenon. From coincident in situ measurements all relevant meteorological parameters are characterized. Ambient humidity had been close to ice saturation. From this a non-exhaust formation of ice can be excluded. Also, the mechanism of non-entrainment of exhaust into the vortices is excluded of being responsible for the observed early onset of the central wake (870 m behind aircraft). The central wake onset originates from early detrainment starting after a 3/4 roll-up period of the vortex. Baroclinic and shear forces do not contribute to the detrainment (imaginary Brunt-Vaisala frequency -0.00003 inverse seconds squared, shear -0.01 inverse seconds, bulk Richardson number -0.3). Ambient turbulence had been fully developed with an inertial range and locally isotropic turbulence for wavenumbers 0.004 - 0.1 radians/m. The eddy dissipation rate 7.4 ± 0.00005 meters squared per seconds cubed exceeds the values found over the North Atlantic flight corridor at cruising altitude by a factor of 1000. Turbulence was identified as the dominating detrainment mechanism.

Suthon, P. B.

"INTERACTION OF A VORTEX PAIR WITH A FREE SURFACE: MEASUREMENTS AND COMPUTATIONS"

M.S. Thesis, June 1990, Naval Postgraduate School, Monterey, CA

An investigation of the interaction of two-counter-rotating vortices with a free surface has been undertaken. Experiments were carried out in two water basins and in a long towing tank using measurements, flow visualization, and an infrared camera. The results have shown that all types of vortex pairs over a wide range of Froude Numbers give rise to three-dimensional surface disturbances, known as scars and striations. The striations are a consequence of the short wavelength instability inherent to the vortex pair itself. The scars are transported outward by the vortex pair and are comprised of a constellation of coherent vortical structures (whirls). The experiments have provided sufficient understanding of the physics of the phenomenon and led to the development of a numerical model based on vortex dynamics. This model proved to be capable of explaining the physical processes involved in the evolution of the three-dimensional footprints of the vortex pair.

Sutkow Jr., M. L., Pandey, A., McCrink, M. H. and Gregory, J. W.

"ROTOR WAKE STRUCTURE DEVELOPMENT IN LOW REYNOLDS NUMBER CONDITIONS"

AIAA Paper 2018-1830, January 2018, Kissimmee, FL.

Two-component particle image velocimetry (PIV) and performance measurements were used to study tip vortex and wake sheet development on small-scale rotor blades. Unique features of the wake structures have been associated with the aerodynamic inefficiency of rotors operating in low Reynolds number conditions. This work seeks to explore how these features develop over a range of Reynolds numbers by varying the rotational speed and size of the blades. A vortex identification scheme was used to locate downstream tip vortices and characterize their aperiodic wandering behavior for different operational conditions. Development of tip vortices was found to depend significantly on the thrust coefficient making the comparison at different Reynolds numbers challenging. When observed at constant wake age, the wandering motion of the vortices behaved independently of Reynolds number scaling. The normalized standard deviation of the tip vortex wander was found to match well with historically observed trends, but a difference in magnitude suggests aperiodicity depends strongly on blade number instead.

Suttie, D. R., Coton, F. N. and Galbraith, R. A.

"DEVELOPMENT OF AN INDICIAL MODEL OF HELICOPTER TAIL ROTOR ORTHOGONAL BLADE VORTEX INTERACTION"

AIAA Paper No. 2005-0469, Reno, NV, January 2005

This paper describes the development of an indicial model of orthogonal blade vortex interaction. This type of interaction can be experienced by the tail rotor of a helicopter in certain flight states and is a known noise generator. The work uses a substantial database of experimental measurements, made

at the University of Glasgow during a five-year research program, to validate the indicial model predictions. The blade response during orthogonal blade vortex interaction is strongly dependent on the axial flow within the vortex core. Depending on the vortex core size, however, it is likely that only a small proportion of the chord is subject to this cross-flow at any instant in time. In addition, after the initial vortex cutting, the axial flow stagnates quite rapidly. These features present modeling challenges and this is demonstrated by showing that a simple indicial model driven by a classical vortex core model, in which the blade is represented as a point, significantly over-predicts the blade response. It is also shown that a more sophisticated representation, in which the chordal distribution of cross-flow is accounted for in the indicial model, produces considerably improved predictions. At this stage it becomes apparent that comparison of the model with the experiment is compromised by the three-dimensionality of the measured data. This is explored by numerically simulating the experiment with a vortex wake code. Indicial predictions based on this simulation are found to display many of the essential features of the measured data.

Suzuki, T. and Colonius, T.

"INVERSE-IMAGING METHOD FOR DETECTION OF A VORTEX IN A CHANNEL"

AIAA Journal, Vol. 41, No. 9, September 2003, pp. 1743-1751

A simple vortex-imaging algorithm using a least-square method is considered. The position and the circulation of a vortex convected in a channel are identified from the time history of pressure at a limited number of points on the wall. The capabilities of the algorithm are demonstrated using two-dimensional direct numerical simulations. A few observer points on one side of the wall are sufficient to detect the position and the circulation of a compact vortex to a reasonable degree of accuracy. An advanced algorithm can even detect two nearby vortices to the same degree of accuracy. Because the algorithm assumes a point vortex solution, the accuracy of the detection deteriorates as the vorticity distribution spreads.

Sviridenko, Y. N.

"APPLICATION OF THE METHOD OF GENERALIZED VORTEX PARTICLES TO SIMULATION OF AN AIRCRAFT VORTEX WAKE"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 24-32

The paper considers the application of the vortex particle method to solve the problem on the formation of the vortex wake behind an aircraft. To obtain the shape of the vortex wake, a two-dimensional unsteady problem on the motion of vortex particles in self-induced flowfield is solved. In this formulation, time plays a role of the third spatial coordinate. The application of the vortex particle method allows one to control during the problem's solution the conservation of the integrals of the system's motion: momentum, angular momentum, and energy of the vortex system. Developed in the work was an algorithm of vortex particles merging and the formation of cores with allowance for the

conservation of the system's first integrals. Examples are presented of the application of the method to several problems on the roll-up of the vortex sheet behind an aircraft. As initial vorticity distributions, analytical relationships and distributions were used, which were obtained in computing flow around a complete aircraft configuration with a panel method.

Sviridenko, Y. N.

"AN INVESTIGATION OF NUMERICAL SCHEMES OF DIFFERENT ACCURACY ORDERS FOR DETERMINATION OF THE VORTEX SHEET'S SHAPE IN THE NEAR WAKE BEHIND AN AIRCRAFT"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 60-65

Addressed in this paper is the problem of modeling the vortex wake behind an aircraft's wing. For computing load distribution and circulation of the vortices shed from the wing's trailing edge a panel method of symmetric singularities is used. Then, the spanwise circulation distribution obtained is used for determining circulation values of individual vortex filaments representing the vortex sheet behind an aircraft. The shape of the vortex sheet is obtained in the core of an iteration process by way of orienting the vortex filaments along local streamlines. The primary objective of this work is an analysis of numerical schemes of different orders of accuracy used in modeling the vortex sheet behind the wing. First-, second-, and third-order accurate schemes were considered. As test configurations, two geometries were considered: an isolated wing and a wing with a part span slotted flap. Effects of the numerical schemes' parameters on the convergence of the iteration process were also analyzed.

Swanson, A. A.

"APPLICATION OF THE SHADOWGRAPH FLOW VISUALIZATION TECHNIQUE TO A FULL-SCALE HELICOPTER ROTOR IN HOVER AND FORWARD FLIGHT"

AIAA Paper No. 1993-2140, August 1993, Monterey, CA.

The wide-field shadowgraph flow visualization technique was used for the first time with a full-scale helicopter rotor. This was accomplished during testing of a Sikorsky S-76 main rotor in the NASA Ames National Full-Scale Aerodynamics Complex 80- by 120-Foot Wind Tunnel. Hover, low-speed forward flight, and descent operating conditions were studied. Preliminary results are very promising with rotor wake tip vortex roll-up, inboard wake vorticity, and flow unsteadiness due to test section recirculation effects in hover. Shadowgraphs of blade/vortex interactions were also acquired. Simultaneous top and side view shadowgraphs of the rotor wake were acquired by a newly developed synchronized digital imaging system. The imaging system proved to be a highly successful tool which made real-time examination of selected regions of the rotor wake possible.

Swanson, S. M., McCluer, M. S., Yamauchi, G. K. and Swanson, A. A.

"AIRLOADS MEASUREMENTS FROM A 1/4-SCALE TILTROTOR WIND TUNNEL TEST"

25th European Rotorcraft Forum, Paper No. P1, Rome, Italy, September 1999

Blade airloads data were acquired for a 1/4-scale tiltrotor model tested at the Duits-Nederlandse Windtunnel in The Netherlands. For the first time, detailed airloads measurements were acquired for an isolated tiltrotor model utilizing one hundred and fifty dynamic pressure transducers. Simultaneous acoustic measurements were made in a plane below the model rotor to correlate airloads with tiltrotor noise. Rotor performance data and wake geometry data were also acquired. Samples of the airloads data are presented for several key operating conditions. The effects of rotor thrust and model shaft angle on the blade airloads are discussed. Comparisons are made between blade pressure data, acoustic data and laser light sheet results. Negative lift at the blade tip was found over a wide range of conditions for the tiltrotor in helicopter mode. Single and multiple blade-vortex interactions were measured and correlated with acoustic data and measured wake geometry. The data acquired during this test provide a fundamental set of aeroacoustic measurements that can be used to validate tiltrotor analyses.

Swedish, W. J.

"EVALUATION OF THE POTENTIAL FOR REDUCED LONGITUDINAL SPACING ON FINAL APPROACH"

FAA-EM-79-7, August 1977, Mitre Corp., McLean, VA

Reducing the separations between aircraft can improve airport capacity and decrease delays. This report addresses the feasibility of reduced IFR separation standards on final approach, and identifies the characteristics of the ATC system which affect or are affected by the separation standards. This study has been limited to conditions during which wake turbulence is not a factor. Given this assumption, separation reduction will be most limited by the need to avoid simultaneous runway occupancy by successive arrivals. As the interval between landings decreases, so must the time spent on the runway, if dual runway occupancy is to be avoided. For acceptable performance, the average runway occupancy time must be no more than 50 seconds for a 2.5 nmi minimum separation standard or 37 seconds for a 2.0 nmi standard, with the current ATC system. Various technical improvements now under development may make it possible to operate a 2.0 nmi minimum with average runway occupancies as great as 45-50 seconds. Adequate communications and surveillance for the controller, and enforcement of current ATC procedures are also required for operations with reduced separations. An alternative solution to the runway occupancy problem is to use a pair of close-spaced, dependent (dual-lane) runways and alternate arrivals between them. Reduced separation on approach to a single runway cannot be realized until the wake vortex problem is resolved.

Swedish, W. J.

"THE REQUIREMENTS FOR REDUCED IFR SEPARATIONS ON FINAL APPROACH"

Proceedings 25th Conf., Air Traffic Control Assoc., Arlington, VA, October 1980, pp. 39-43

This paper examines the factors which affect the feasibility of reducing IFR standards from a minimum of 3.0 nmi to 2.5 or 2.0 nmi. For those aircraft pairs which are not restricted by wake vortices,

separation reduction is likely to be limited by the rate at which aircraft must go around to avoid simultaneous runway occupancy. The runway occupancy performance required to avoid an unacceptable increase in the go-around rate is determined. The impacts of ATC improvements such as metering and spacing on the runway occupancy requirements and on the controller's decision-making workload are then presented. Alternating arrivals to close-spaced parallel runways are discussed as one means to avoid the constraints of runway occupancy and, possibly, wake vortices. Lastly, it is proposed that further research on reduced separations should address a single specific airport, to narrow the range of variables and thereby facilitate the identification of problems and solutions.

Swirydczuk, J.

"A VISUALIZATION STUDY OF THE INTERACTION OF A FREE VORTEX WITH THE WAKE BEHIND AN AIRFOIL"

Experiments in Fluids, Vol. 9, Issue 4, June 1990, pp. 181-190.

The two-dimensional interaction of a single vortex with a thin symmetrical airfoil and its vortex wake has been investigated in a low turbulence wind tunnel having velocity of about 2 m/s in the measuring section. The flow Reynolds number based on the airfoil chord length was 4,500. The investigation was carried out using a smoke-wire visualization technique with some support of standard hot-wire measurements. The experiment has proved that under certain conditions the vortex-airfoil-wake interaction leads to the formation of new vortices from the part of the wake positioned closely to the vortex. After the formation, the vortices rotate in the direction opposite to that of the incident vortex.

Swithenbank, J. and Chigier, N. A.

"VORTEX MIXING FOR SUPERSONIC COMBUSTION"

Proceedings 12th Symposium Combustion Inst., 1969, Pittsburg, PA, pp. 1153-1162.

Fundamental concepts of mixing and combustion theory are examined to define an optimum system. By analogy with the familiar parameter 'combustion intensity' a 'mixing intensity' is defined as the total mass of fuel and air mixed per unit time, volume, and density. Mixing intensity is related to the mean kinetic energy of turbulence generated in a mixing system. The efficiency of generation of turbulence is defined by the ratio of the kinetic energy of turbulence generated to the kinetic energy loss from the mean flow. Bluff body mixers are compared with turbulent jet mixers, and turbulence intensities are determined as a function of fuel/air ratio and jet-to-stream-velocity ratio. For turbulence generated by a baffle system or by jets, the mixing intensity is shown to be proportional to the rms velocity and the square root of the number of sources. Substantial increases in mixing rates can be obtained by applying a swirling motion to the central fuel jet. Radial and axial pressure gradients are set up which, in the case of strong swirl, result in reverse flow along the axis. Empirical equations for velocity decay, mass entrainment, and angle of jet expansion are given as functions of the degree of swirl. However, further work is needed on the behavior of these parameters in an external flow field. For the combustion chamber of a scramjet, the degree of swirl imparted to the fuel can be altered readily by varying the

proportion of fuel introduced axially and tangentially into the swirl chamber. The rate of mixing, angle of jet expansion, and the size of internal reverse-flow can all be controlled by variation of the swirl number. With the ability to initiate and remove the reverse-flow region, an optimized combustion system could operate efficiently from low-subsonic to high-supersonic Mach numbers.

Switzer, G. F.

"VALIDATION TESTS OF TASS FOR APPLICATION TO 3-D VORTEX SIMULATIONS"

NASA CR-4756, October 1996, Research Triangle Institute, Research Triangle Park, NC.

Direct analytical solutions can be useful in validating the core formulation of numerical systems. In this document an exact analytical solution to the Navier-Stokes equation is compared to the numerical results from the three-dimensional Terminal Area Simulation System (TASS). This exact solution, of which the derivation is included, is for Beltrami type flow. Direct comparison of TASS to the analytical Beltrami solution is then used in evaluating the accuracy of TASS.

Switzer, G. F.

"TWO-DIMENSIONAL SIMULATION OF WAKE VORTEX INTERACTION FROM MULTIPLE AIRCRAFT"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 212-222

This numerical experiment investigates the significance of wake interaction from multiple aircraft in the region of the runway threshold. The study is chosen from the 1995 Memphis observations of cases 1493 to 1496 because of close spacing and varied strengths of the wake vortex systems. The observed environmental input conditions are of weak crosswinds with a mean value of 1 m/s. The model vortex systems are injected at times and altitudes corresponding to that of the actual aircraft. A video of potential temperature and vorticity shows the dynamics of the vortex interaction. The observations from the video are that vortex movement may change direction from downwind to upwind due to influence of other vortex systems and vortices from different aircraft may couple to produce new vortex systems. However, the interaction from multiple vortex systems did not create significant departures from what was predicted with an isolated vortex system. Finally, the trajectory of altitude and lateral position is compared for Memphis case 1494 and 1496 showing good agreement.

Switzer, G. F. and Proctor, F. H.

"NUMERICAL STUDY OF WAKE VORTEX BEHAVIOR IN TURBULENT DOMAINS WITH AMBIENT STRATIFICATION"

AIAA Paper No. 2000-0755, Reno, NV, January 2000.

A three-dimensional large eddy simulation model is used to investigate the sensitivity of ambient stratification with turbulence on the behavior of aircraft wake vortices. Modeled ambient turbulence

levels range from very weak to moderate, and stratification levels range from strongly stable to unstable. The results of profound significance from this study are: 1) very little sensitivity between vortex linking time and the level of stratification, 2) the mean vortex separation remained nearly constant regardless of stratification and turbulence (at least prior to linking), 3) the wake vortices did not rise regardless of the level of stratification, and 4) for very strong stratification, the vortex stopped descending and quickly dissipated even before vortex linking could occur. These results are supported by experimental data and are contrary to conclusions from other numerical studies that assume laminar flow and/or relatively-low Reynolds numbers.

Switzer, G. F. and Proctor, F. H.

"WAKE VORTEX PREDICTION MODELS FOR DECAY AND TRANSPORT WITHIN STRATIFIED ENVIRONMENTS"

AIAA Paper No. 2002-0945, Reno, NV, January 2002

This paper proposes two simple models to predict vortex transport and decay. The models are determined empirically from results of three-dimensional large eddy simulations, and are applicable to wake vortices out of ground effect and not subjected to environmental winds. The results from the large eddy simulations assume a range of ambient turbulence and stratification levels. The models and the results from the large eddy simulations support the hypothesis that the decay of the vortex hazard is decoupled from its change in descent rate.

Switzer, G. F., Proctor, F. H., Ahmad, N. N. and Duparcmeur, F. M. L.

"AN IMPROVED WAKE VORTEX TRACKING ALGORITHM FOR MULTIPLE AIRCRAFT"

AIAA Paper No. 2010-7993, Toronto, Canada, August 2010.

The accurate tracking of vortex evolution from Large Eddy Simulation (LES) data is a complex and computationally intensive problem. The vortex tracking requires the analysis of very large three-dimensional and time-varying datasets. The complexity of the problem is further compounded by the fact that these vortices are embedded in a background turbulence field, and they may interact with the ground surface. Another level of complication can arise, if vortices from multiple aircrafts are simulated. This paper presents a new technique for post-processing LES data to obtain wake vortex tracks and wake intensities. The new approach isolates vortices by defining 'regions of interest' (ROI) around each vortex and can identify vortex pairs from multiple aircraft. The paper describes the new methodology for tracking wake vortices and presents application of the technique for single and multiple aircraft.

Swol, C. D.

"SIMULATION-BASED ANALYSIS OF WAKE TURBULENCE ENCOUNTERS IN CURRENT FLIGHT OPERATIONS"

MS Thesis, August 2009, Virginia Polytechnic Institute and State University, Blacksburg, VA.

One way to address the need for increased airspace system capacity is to reduce the separation requirements between aircraft in-flight. A key limiting factor to any reduction in separation is wake turbulence. The potential for aircraft to encounter wake turbulence poses a threat to both safety as well as increased efficiency. This research effort seeks to develop a model that can be used to evaluate the potential for wake encounters in today's flight operations, as well as serve as a tool for evaluating future reduced separation scenarios. The wake encounter model (WEM) achieves this goal by integrating results from NASA's TDAWP wake turbulence prediction model with a flight operations model based on radar flight track data. Unique in this model's design, is the ability to evaluate the potential for wake encounters throughout the terminal area versus previous research which has largely been restricted to areas near the runway. Expanding the model's reach provides not only a more thorough analysis of potential wake encounters, but also creates an effective tool for evaluating future reduced separation scenarios. The WEM model was used to evaluate operations at three metropolitan airspaces in the United States: Atlanta, Los Angeles and New York. The results from these model runs indicated that potential wake encounters in today's operations were few. More importantly, the results from the WEM create a baseline for wake turbulence exposure in today's system, by which future scenarios can be compared against as part of any comprehensive reduced separation safety analysis.

Syal, M. and Leishman, J. G.

"MODELING OF BOMBARDMENT EJECTIONS IN THE ROTORCRAFT BROWNOUT PROBLEM"

AIAA Journal, Vol. 51, No. 4, April 2013, pp. 849-866.

The modeling of bombardment ejections, as they affect the uplift of dust particles and the formation of a brownout dust cloud generated by a rotorcraft in ground effect operations, is discussed. Bombardment ejections take place when a previously suspended particle in the flow collides with a sediment bed and ejects many more particles, leaving a crater behind. A model, based in part from research in aeolian sediment transport, was developed to better represent the mechanisms of bombardment-induced particle ejections during rotorcraft brownout conditions. This method was then coupled to a Lagrangian solver for the rotor flow and a Lagrangian particle dynamics simulation. It is shown how bombardment can play a critical role in the uplift and entrainment of smaller-sized particles from the underlying bed below a rotor. In particular, it is shown how the rotor blade tip vortices and/or regions of flow recirculation near the rotor can eject many particles by bombardment, resulting the rapid development of intense dust clouds. The formation of vortex wake bundling ahead of the rotor disk was shown to provide the conditions particularly ripe for the ejection and uplift of large quantities of dust particles by means of bombardment mechanisms.

Sychev, V. V.

"ASYMPTOTIC THEORY OF VORTEX BREAKDOWN"

Rossiyskaya Akademiya Nauk, Izvestia, Mekhanika Zhidkosti I Gaza, ISSN 0568-5281, No. 3, June 1993, pp. 78-90

The phenomenon of vortex breakdown is investigated by using an asymptotic analysis of a system of Navier-Stokes equations at large Reynolds numbers. A criterion for vortex breakdown is formulated; the flow structure is described as a whole and in the direct vicinity of the breakdown point. It is shown that vortex breakdown is a two-stage process, and a description of each stage is provided. [In Russian.]

Sydney, A. J. and Milluzzo, J. I.

"EFFECTS OF VORTEX NUMBER ON THE DEVELOPMENT OF VERTICALLY DOMINATED WAKES"

AIAA Paper 2018-4158, June 2018, Atlanta, GA.

The interaction of vortical flows is prominent throughout wakes created by vehicles that require lifting surfaces (e.g., airplanes, rotorcraft, submarines, etc.). While the interactions between the two vortices produced by a single lifting surface have been investigated, wakes that include a third and fourth vertically displaced vortex of varying strength and direction of rotation are not as well understood. The additional vortices produced by low aspect ratio, perpendicular lifting surfaces will fundamentally change the vortex dynamics and mechanics of vortex breakdown. In fact, the development of the vortices will be affected by several wake characteristics, including vortex direction of rotation, vortex strength, vortex spacing, and number of vortices. The goal of the present work is to provide an understanding of the vortically dominated wake consisting of up to four spatially displaced vortices that are produced by low aspect ratio lifting surfaces. Wake features such as vortex development, vorticity distribution, trajectories, and vortex strength are being investigated. These wake characteristics are studied experimentally using Particle Image Velocimetry (PIV) in the United States Naval Academy (USNA) Closed Circuit Wind Tunnel (CCWT). This paper focuses on the results examining the effects of number of vortices. The results show that number and distribution of vortices significantly affect not only the vortex trajectories but the overall development of the downstream wake.

Szkatula, L., Zouaoui, Z. and Grant, R. J.

"DYNAMICS OF VORTICAL FLOWS INDUCED BY SWEEPED-NOTCHED WINGS IN AIRCRAFT WAKE SIMULATIONS"

J. Aircraft, Vol. 45, No. 2, March-April 2008, pp. 448-460

The motivation behind the present investigations is the alleviation of vortex wake hazard. The influence of wingtip geometry modifications on the near-field wake behind swept-notched wings is investigated up to 24 span-lengths, using computational fluid dynamics, 3-D parallel simulations are run at a chord-based Reynolds-number of $5.34 \times 10,000$. The effectiveness of notched wing modifications on wake properties is assessed via comparison with conventional and original notched wings. Current results are promising: the tip and flap vortices produced by the swept-notched wings remain distinct

and unmerged, unlike circulations and vorticity values that are substantially lower than the original notched wing. Numerical data clearly indicate that such geometrical combinations break apart the concentrated area of streamwise vorticity shed by the wing into three or more less intense regions, significantly reducing the wake strength and induced rolling moment, and affecting the location and merging process of the overall wake system.

Szymendera, C. J.

"COMPUTATIONAL FREE WAKE ANALYSIS OF A HELICOPTER ROTOR"

M.S. Thesis, May 2002, Pennsylvania State University, Philadelphia, PA

One of the most important issues in understanding the behavior of rotorcraft is the accurate prediction of the rotor wake. Understanding the complex nature of the wake is necessary for the prediction of such factors as blade loading acoustics, and vibration. A free wake vortex lattice method was used to predict the wake structure and blade loading for a rotor in arbitrary motion. The blades were modeled as flat plates, and ring vortices were distributed on the surface of the blades. As the blades rotated, vortices were shed into the wake and then moved with a local velocity induced by the effects of the vortices on the blades and in the wake. The wake was allowed to freely deform over time into its natural structure. The lift was determined from the strength of each vortex on the blade, calculated by applying the boundary condition of no flow normal to the blade. On a helicopter in forward flight, the advancing blades usually experience high Mach numbers at the tip. Therefore, it is important to be able to accurately predict the blade loading in compressible flow. The free wake method, though, calculates induced velocities using the Biot-Savart Law, which is only applicable to incompressible flow. A Prandtl-Glauert correction was applied then to the Biot-Savart Law, which allowed the code to accurately model compressible flow. The code was validated using two experimental hover cases, one in which the flow was entirely incompressible and one in which the flow was compressible at the tips, and then extended to handle any arbitrary motion of the helicopter.

Taamallah, S.

"A QUALITATIVE INTRODUCTION TO THE VORTEX-RING-STATE, AUTOROTATION, AND OPTIMAL AUTOROTATION"

NLR-TP-2010-282, May 2011, National Aerospace Laboratory, Amsterdam, The Netherlands.

The main objective of this paper is to provide the reader with some qualitative insight into the areas of Vortex-Ring-State (VRS), autorotation, and optimal autorotation. First this paper summarizes the results of a brief VRS literature survey, where the emphasis has been placed on a qualitative description of the following items: conditions leading to VRS flight, the VRS region, avoiding the VRS, the early symptoms, recovery from VRS, experimental investigations, and VRS modeling. The focus of the paper is subsequently moved towards the autorotation phenomenon, where a review of the following items is given: the maneuver, the height-velocity zones, and factors affecting autorotation. Finally, the paper

concludes by providing a literature survey relative to single-engine helicopter optimal autorotation, and its associated problem formulation as a nonlinear, constrained, optimal control problem.

Taamallah, S.

"A QUALITATIVE INTRODUCTION TO THE VORTEX-RING-STATE, AUTOROTATION, AND OPTIMAL AUTOROTATION"

36th European Rotorcraft Forum, Paper 089, September 2010, Paris, France.

The main objective of this paper is to provide the reader with some qualitative insight into the areas of Vortex-Ring-State (VRS), autorotation, and optimal autorotation. First this paper summarizes the results of a brief VRS literature survey, where the emphasis has been placed on a qualitative description of the following items: conditions leading to VRS flight, the VRS region, avoiding the VRS, the early symptoms, recovery from VRS, experimental investigations, and VRS modeling. The focus of the paper is subsequently moved towards the autorotation phenomenon, where a review of the following items is given: the maneuver, the height-velocity zones, and factors affecting autorotation. Finally, the paper concludes by providing a literature survey relative to single-engine helicopter optimal autorotation, and its associated problem formulation as a nonlinear, constrained, optimal control problem.

Tabib, M., Rasheed, A. and Fuchs, F.

"ANALYZING COMPLEX WAKE-TERRAIN INTERACTIONS AND ITS IMPLICATIONS ON WIND-FARM PERFORMANCE"

The Science of Making Torque from Wind 2016, published in IOP Journal of Physics: Conference Series Vol. 753, 2016, pp. 032063-1 - 032063-12.

Rotating wind turbine blades generate complex wakes involving vortices (helical tip-vortex, root-vortex etc.). These wakes are regions of high velocity deficits and high turbulence intensities and they tend to degrade the performance of down-stream turbines. Hence, a conservative inter-turbine distance of up-to 10 times turbine diameter (10D) is sometimes used in wind-farm layout (particularly in cases of at terrain). This ensures that wake-effects will not reduce the overall wind-farm performance, but this leads to larger land footprint for establishing a wind-farm. In-case of complex-terrain, within a short distance (say 10D) itself, the nearby terrain can rise in altitude and be high enough to influence the wake dynamics. This wake-terrain interaction can happen either (a) indirectly, through an interaction of wake (both near tip vortex and far wake large-scale vortex) with terrain induced turbulence (especially, smaller eddies generated by small ridges within the terrain) or (b) directly, by obstructing the wake-region partially or fully in its own-path. Hence, enhanced understanding of wake-development due to wake-terrain interaction will help in wind farm design. To this end the current study involves: (1) understanding the numerics for successful simulation of vortices, (2) understanding fundamental vortex-terrain interaction mechanism through studies devoted to interaction of a single vortex with different terrains, (3) relating influence of vortex-terrain interactions to performance of a wind-farm by studying a multi-turbine wind-farm layout under

different terrains. The results on interaction of terrain and vortex has shown a much faster decay of vortex for complex terrain compared to a flatter-terrain. The potential reasons identified explaining the observation are (a) formation of secondary vortices in ow and its interaction with the primary vortex and (b) enhanced vorticity diffusion due to increased terrain-induced turbulence. The implications of this vortex-terrain interactions on wind-farm performance is observed by comparing two LES simulations of a multi-turbine wind-farm layout (in real actual complex terrain and a made-up at terrain scenario) with the observed annual power data at the actual wind-farm. The comparison reveals drop in power production due to terrain and wake effects for flatter terrain case. The insights from this study can serve as a step towards enhancing wake-dissipation through either artificial obstruction or artificial terrain modifications.

Tabrizi, A. T., Wassaf, H. S., Wang, F. Y. and Clark, K. L.

"METEOROLOGICAL TOWER REPORT"

Report DOT/VNTSC-FAA-07-06, November 2008, Volpe National Transportation Systems Center, Cambridge, MA.

The Campbell Scientific CSAT3 sonic anemometers are chosen as the turbulence sensor. To qualify CSAT3, wind velocity measurements from the sonic and traditional three-axis propeller anemometers were made on a tower and compared. The data analysis was done in the framework of linear regression on the entire dataset, and special attentions were paid to probe interference, frequency response, sensor thresholds and angular response of the instruments. The result of this in-situ calibration against propellers demonstrated that the sonic anemometer chosen measured the low frequency wind fluctuation correctly, thereby establishing a necessary step in qualifying the sensor for turbulence measurements. To establish a reliable means of monitoring the health of the entire measurement chain as well as identifying periods of questionable data, hourly based linear regression and root-mean-square error statistics are explored. The method demonstrated its ability to efficiently isolate specific erroneous data periods, and examples of this utility were illustrated. The calibration process concluded that the entire measurement system chain involving the sonic anemometers has been qualified, and capable of supporting the meteorological data collection needs of the mid-term phase of the wake turbulence program.

Tadghighi, H.

"CURRENT ASSESSMENTS OF BOEING-MESA CFD TOOLS FOR APPLICATIONS TO ROTOR PERFORMANCE/WAKE COMPUTATION IN HOVER FLIGHT"

Proceedings of the ARO Rotorcraft Wake Prediction Basic Research Workshop, March 2009, Georgia Institute of Technology, Atlanta, GA, p. 79.

The presentation will provide detailed information pertaining to the coupling techniques of Vortran-M model developed originally by Professor Brown (University of Glasgow, UK) with the OVERFLOW solver. Under this approach, the main goal is to tightly couple the techniques used in the Vorticity

Transport Model (VTM) with the OVERFLOW solver to enhance the rotor wake capturing for both hover and forward flight regimes, specially BVI flows. As the result, the computational grid needed for a typical rotor aerodynamics performance computation can be kept to an optimum size in comparison to the historically very large grid size needed in the past to obtain a reasonable estimation of rotor, say, Figure-of-Merit values. This approach will also offer a reduction in both memory requirements and CPUs resources. Therefore, it enables a much larger run matrix to be performed over a reasonable time frame. In its final form, it is expected that the newly developed OV_VTM solver will become a more practical CFD tool for preliminary design applications. Further, the past results obtained for 500E aircraft main rotor performance using OVERFLOW solver will be presented to enable a fair assessment of its capabilities in computing the rotor hover performance in the absent of the VTM model.

Tadmor, G.

"OBSERVERS AND FEEDBACK CONTROL FOR A ROTATING VORTEX PAIR"

IEEE Transactions on Control Systems Technology, Vol. 12, No. 1, January 2004, pp. 36-51

An observer is developed to estimate and to feedback-regulate the location of the vorticity centroid and the mutual distance of an interacting, same sign vortex pair. The combination of the crude approximation provided by very low-order vortex models, and high nonlinearity, even at that level, seem to make sensitive gain scheduling and high-order vector field derivatives in geometrical observer design methods, ill suited for the system at hand. This paper explores possibilities for dynamic extraction of needed information directly from leading frequencies and phasors of a sensor signal, using an extended Kalman filter. Intended advantages include simplicity, robustness, and the filtering of unmodeled dynamics.

Taguchi, M., Semba, N., Mori, K., Nakamura, Y. and Ishiko, K.

"EXPERIMENTAL STUDY ON JET BLAST AT LABORATORY SCALE"

Journal of Energy and Power Engineering, Vol. 8, 2014, pp. 1386-1392.

The flow field of 3D (three-dimensional) wall-jet is investigated. Jet-blast from airplane is simulated by wall-jet setup using a sonic nozzle at a laboratory scale. Far field velocity and fluctuation distributions are measured by using X-type hot wire anemometer at four measurement planes. As a result, the flow properties of streamwise component are consistent with data which are obtained in previous researches. The secondary flow is also measured on each measurement plane. Reynolds stresses are analyzed from the fluctuation of the secondary flow. The law of similarity is observed in the dimensionless distributions of mean velocity and fluctuation. However, the distributions in nearer field (i.e., in the measurement plane at $X/D = 100$) tend to disobey the similarity law, especially in the cases of fluctuation. It seems that Jet-blast is not fully developed by reaching $X/D = 100$. The experimental results are compared with computational results which are obtained by CFD (computational fluid dynamics) with SST (shear-stress transport) turbulence model. And it is shown that the results by the simulation with SST turbulence model do not follow the similarity law. The

present database of the Reynolds stresses is critically important for development of a new turbulence model of RANS (Reynolds-averaged Navier-Stokes) simulations on wall-jet.

Taira, K. and Colonius, T.

"ON THE EFFECT OF TIP VORTICES IN LOW-REYNOLDS-NUMBER POST-STALL FLOW CONTROL"

AIAA Paper 2009-0376, Jan. 2009, Orlando, FL

We numerically investigate the application of steady blowing to three-dimensional stalled flows around low-aspect-ratio rectangular flat-plate wings at a Reynolds number of 300. The objective of this study is to explore techniques to enhance lift by directly modifying the dynamics of the wake vortices. Out of various combinations of forcing location and direction considered, we identify two configurations that provide significant lift enhancement. In these cases, actuation appears to strengthen the tip vortices for increased downward induced velocity upon the leading-edge vortices. This in turn moves the low-pressure core directly above the top surface of the wing to greatly enhance lift.

Taira, K., Rowley, C. W., Colonius, T. and Williams, D. R.

"LIFT ENHANCEMENT FOR LOW-ASPECT-RATIO WINGS WITH PERIODIC EXCITATION"

AIAA Journal, Vol. 48, No. 8, August 2010, pp. 1785-1789.

To enhance lift on low-aspect-ratio rectangular flat-plate wings in low-Reynolds-number post stall flows, periodic injection of momentum is considered along the trailing edge in this numerical study. The purpose of actuation is not to reattach the flow but to change the dynamics of the wake vortices such that the resulting lift force is increased. Periodic forcing is observed to be effective in increasing lift for various aspect ratios and angles of attack, achieving a similar lift enhancement attained by steady forcing with less momentum input. Through the investigation on the influence of the actuation frequency, it is also found that there exists a frequency at which the flow locks on to a time-periodic high-lift state.

Takahashi, H., Yuhara, T., Kanamori, M. and Makino, Y

" STATISTICAL CHARACTERIZATION OF ATMOSPHERIC TURBULENT SCALES IN HOT-DRY AND HOT-HUMID CLIMATES"

AIAA Paper 2019-1869, January 2019, San Diego, CA.

Atmospheric turbulent characteristics were statistically quantified regarding the integral length scale, energy dissipation rate, and turbulence intensity in the surface layer and the troposphere in hot-dry and hot-humid climates at different geographical locations. Meteorological data were collected at each location using ultrasonic anemometers, rawinsonde balloons, and SODARs in collaboration with the NASA Armstrong Flight Research Center and the NASA Langley Research Center during the Sonic Booms

in Atmospheric Turbulence (SonicBAT) projects conducted in 2016 and 2017. Based on various meteorological datasets of wind speed, temperature, and relative humidity, an approach to derive the integral length scale was explored by deriving the energy dissipation rate from those time-series variations. Using two independent methods to derive the energy dissipation rate from autocorrelation analysis and from the fast Fourier transform, unknown coefficients were determined by the best-fitting method so that the two derived values are in agreement. Results indicated that the derived length scales were consistent with those reported in previous studies in their orders. The integral length scales range from 10^0 – 10^3 throughout the surface to the upper air in hot-dry and hot-humid climates. Clear differences were also seen in such turbulent statistics as time cycle depending on relative humidity.

Takahashi, N. and Miyazaki, T.

"INTERACTION BETWEEN A COLUMNAR VORTEX AND EXTERNAL TURBULENCE"

In IUTAM Symposium on Elementary Vortices and Coherent Structures: Significance in Turbulence Dynamics, edited by S. Kida, Springer, The Netherlands, 2006, pp. 31-38.

The interaction between a columnar vortex and external turbulence is investigated numerically. As columnar vortices, the Lamb-Oseen vortex and the q-vortex are used. The columnar vortex is immersed in an initially isotropic homogeneous turbulence field, which itself is produced by a direct numerical simulation of decaying turbulence. Using visualization techniques, we investigate the formation of inhomogeneous fine turbulent eddies around the columnar vortex, vortex-core deformations and the dynamical evolution in the passive scalar field.

Takahashi, N., Ishii, H. and Miyazaki, T.

"THE INFLUENCE OF TURBULENCE ON A COLUMNAR VORTEX"

Physics of Fluids, Vol. 17, March 2005, pp. 035105-1-035105-14.

The interaction between a columnar vortex and external turbulence is investigated numerically. A Lamb-Oseen vortex is immersed in an initially isotropic homogeneous turbulence field, which itself is produced numerically by a direct numerical simulation of decaying turbulence. The formation of inhomogeneous fine turbulent eddies around the columnar vortex and the vortex-core deformations are studied in detail by visualizing the flow field. The initially random turbulent eddies (worms) are wrapped around the columnar vortex and become spirals. Statistical quantities, such as two-point-energy spectra and two-point-ensrophy spectra, are evaluated and compared with the theoretical predictions from rapid distortion theory. The axial velocity correlation dominates near the vortex surface, whereas the radial velocity correlation becomes larger where the worms are wrapped. Where the columnar vortex is strong compared with the external turbulence, external velocity disturbances are blocked by the vortex and they cannot penetrate the vortex core directly, whereas various types of vortex waves (Kelvin waves) are excited.

Takahashi, R. K. and McAlister, K. W.

"PRELIMINARY STUDY OF A WING-TIP VORTEX USING LASER VELOCIMETRY"

NASA/TM-88343, AVSCOM TM 86-A-2, January 1987, Aeroflightdynamics Directorate, US Army Aviation Research and Technology Activity, Ames Research Center, Moffett Field, CA

Measurements have been made in the wake of a semi-span NACA 0015 airfoil with emphasis on the region of the wing tip vortex. The spanwise and streamwise velocity components were measured using a two-component laser Doppler velocimeter. The purpose of the study was to initiate the operation of a laser velocimeter system and to perform preliminary wake measurements in preparation for a more extensive study of the structure and near field development of a tip vortex.

Takahashi, T. T. and Delisle, M. R.

"(UN)STABILIZED APPROACH -- AN INTRODUCTION TO DYNAMIC FLIGHT CONDITIONS DURING TAKEOFF AND LANDING CLIMB"

AIAA Paper 2018-3500, June 2018, Atlanta, GA.

In this paper, we introduce the mathematics necessary to simulate unstable flight performance -- that is flight with an inadvertent change in speed, altitude or flight path. Using typical aircraft aerodynamic and propulsion data, representing a configuration like the A320, we perform trade studies to understand the weight and configuration effects of 'out-of-trim' flight during takeoff and landing climb. We found that pilots could lose airspeed quite quickly. During AEO second segment climb, a 1-degree error in trimmed angle-of-attack causes the aircraft to lose -0.6 knots per second. During OEI second segment climb, a 3-degree angle-of-attack trim error causes the aircraft to lose speed at -3.5 knots per second. It would stall after 5 seconds of out-of-trim flight.

Takeshime, Y., Misaka, T., Obayashi, S., Holzaepfel, F., Kato, H., Takahashi, S. and Fujishiro, I.

"TOPOLOGICAL APPROACH TO MULTISENSORY REALIZATION OF WAKE TURBULENCE"

AIAA Paper 2014-2335, June 2014, Atlanta, GA.

It is important to analyze the process of wake turbulence collapse to avoid serious accidents. In this study, we propose a topology-based multisensory realization method that allows observers to comprehend the behavior of wake turbulence phenomena in more intuitive manner. We propose the use of adaptive visual transfer functions as well as haptic transfer functions with three degrees of freedom to produce three-dimensional forces, which allow the identification of the location and strength of a target vortex. We evaluate the effectiveness of our method using a time-varying three-dimensional wake turbulence dataset.

Tam, K. K.

"A NOTE ON THE FLOW IN A TRAILING VORTEX"

J. Engineering Mathematics, Vol. 7, January 1973, pp. 1-6

It is shown that if the equations governing the fluid motion in a trailing vortex are linearized more than one solution can be constructed. Within the framework of the linear theory, there is no criterion to determine which solution is to be used. To clarify the situation, the Navier-Stokes equations are formulated in parabolic coordinates, and asymptotic solutions are sought which are valid for downstream. It is found that the axial velocity defect decays algebraically.

Tamura, E., Itoh, H., Nigim, H. H. and Koyama, H. S.

"EXPERIMENTAL INVESTIGATION OF A TORNADO-LIKE VORTEX USING A PARTICLE IMAGE VELOCIMETRY"

19th International Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics, July 2018, Lisbon, Portugal.

A simple, small size vortex generator has been constructed to develop the structure and behavior of the various type vortices, where many vortices are unsteady. An artificial tornado-like vortex is described in this paper. The flow field measurements were made by using a particle image velocimetry (PIV) technique. Main hardware components of the PIV system are a dual-pulse laser illumination system with high repetition rate, a high-speed, high-resolution digital camera and a tracer seeding system. The PIV system was installed in a clean room. In the present PIV system, the accuracy of the velocity is dependent the accuracy of the time interval between the 1st and 2nd laser emissions, i.e., the pulse separation. And, it is very important that the timings of the 1st and 2nd laser emissions suit the 1st and 2nd exposure times to the camera sensor, respectively. Scrutinizing the characteristics of the pulse laser and digital camera, the dual-pulse laser PIV with the pulse separation of 1.00 microseconds was established. In the present experiments the Reynolds number Re and the swirl ratio S were used as the experimental parameters. The working fluid is discharged from the decompression chambers of the vortex generator by an electrical blower. By adjusting the blower power supplied, it is possible to change Re between 131 and 895. Also, by adjusting only the location of partition, S can be changed between 1.48 and 14.7. Under the conditions of Re and S , the vortex breakdown phenomenon including two or more axial bubbles and an annulus vortex is observed. For the higher S , a complicated tornado-like vortex including two or three subsidiary vortices is also observed near the partition surface simulated the ground of the earth. The radial distribution of the static pressure on the partition surface for the cases of the various Re and S are measured, and compared with the distributions estimated using the azimuthal velocity profiles in the axial-cross plane at close vicinity of the partition surface, measured by the PIV.

Tan, J. and Wang, H.

"HIGHLY EFFICIENT UNSTEADY PANEL TIME-MARCHING FREE WAKE FOR AERODYNAMICS OF ROTORCRAFT"

Journal of Aircraft, Vol. 51, No. 1, January-February 2014, pp. 54-61.

A highly efficient unsteady panel time-marching free wake is established to achieve fast and accurate prediction of the unsteady aerodynamics of a helicopter. The unsteady panel method is used to calculate the airload of rotor blades, and the free-wake method is applied to simulate the dynamics of rotor wake. The two methods are tightly coupled by convecting panels to vortex filaments, and the rotor wake is divided into three parts to reduce the computational cost. The first is shed wake indicated by doublet panels. The second is near-wake filaments, which are described by a series of vortex filaments attaching to the shed wake. The third is far-wake filaments connecting to the near-wake filaments. A velocity-field integration technique is adopted to overcome the singularity problem during the interaction of the rotor wake with blades. Helicopter rotors including the Caradonna-Tung and the AH-1G rotors are simulated in hover and forward flight to validate the accuracy and efficiency of the present approach. The predicted blade pressure and load distribution agree well with the measured data and computational-fluid-dynamics results in hover and low-speed forward flight. Compared to computational fluid dynamics and the traditional panel/vortex-rings free-wake method, the present method is more efficient.

Tan, K. J. B., Wang, P. C. and Srigrarom, S.

"LOW-SPEED POST-STALL WING WAKE IMPINGEMENT ON HORIZONTAL STABILIZER OF THE COMMON RESEARCH MODEL"

AIAA Paper 2018-3898, June 2018, Atlanta, GA.

Results from Reynolds-Averaged computational studies of the span-wise flow field between the horizontal stabilizer and wing of the NASA Common Research Model are presented. It is observed early on that the horizontal stabilizer is engulfed at multiple post-stall angles due to the vertical extent of the wings wake. Discernible flow patterns can be observed such as an up wash and a weak inboard wake vortex that originates from the wing inboard section. The up wash can be attributed to the kink in the wing trailing edge, known as the Yehudi break, which also causes the wake to display characteristic features. As the span-wise extent of the break's location is close to the stabilizer, results suggest levels of interaction between this up wash together with the weak inboard wake vortex. A shift in the inboard wake vortex can also be observed between the presented range of angles of attack. To offer insight on this, results follow velocity contours and vector fields of the wake through these two post-stall angles at 14 degrees and 16 degrees, just forward of the horizontal stabilizer and along stream-wise stations between the wing and tail.

Tanaka, Y., Otsu, K., Kawaguchi, T. and Tsuji, Y.

"EXPERIMENTAL STUDY OF THE INTERACTION BETWEEN BURGERS VORTEX AND A SOLID PARTICLE USING 2D PIV MEASUREMENT"

Journal of JSEM, Vol. 9, Special Issue, 2009, pp. 17-20.

In recent years, many researchers study on characteristics concentrations of particles in turbulent flows. However, it is difficult to observe experimentally interaction between the particles and turbulent vortices because of strong nonlinearity of turbulence. In the present study, we focus on the elementary step of an interaction between single vortex tube and a solid particle in a solid-liquid two-phase flow. Burger's vortex is chosen as single vortex tube. Burger's vortex is the simplest model of turbulence.

Tanaka, Y., Tsuji, T. and Tanaka, T.

"INTERACTION BETWEEN A BURGERS VORTEX AND WAKE VORTEX STRUCTURE GENERATED BY A SETTLING PARTICLE"

Journal of JSEM, Vol. 9, Special Issue, 2009, pp. 1-6.

In the present study, interactions between a single particle and a single Burgers vortex are observed by using 2D-PIV measurements as elementary interactions for modeling particle-laden turbulent flows. We focus on the interaction between a Burgers vortex and wake structure generated by a settling particle. It is found that the interaction between the vortices shed from the particle and the Burgers vortex induces the large fluctuation in the circulation of the vortex. Moreover, fragmentation and emergence of the Burger's vortex core are observed.

Tang, C. C. K., Leung, R. C. K. and Ko, N. W. M.

"INTERACTION OF TWO PERTURBED VORTEX RINGS WITH PHASE DIFFERENCE"

13th Australasian Fluid Mechanics Conference, December 1998, Monash University, Melbourne, Australia.

A numerical study of interaction of two coaxial weakly perturbed vortex rings with phase difference 90 degrees and without 0 degrees is reported. The model of the vortex rings is generated by thin vortex filament and their evolution is solved by means of three-dimensional vortex blob method. Phase difference of the two vortex rings is an important parameter to their evolution and the slip through process.

Tang, S. and Ko, N. W. M.

"SOUND SOURCES IN THE INTERACTIONS OF TWO INVISCID TWO-DIMENSIONAL VORTEX PAIRS"

J. Fluid Mechanics, Vol. 419, 2000, pp. 171-201

The sources of sound during the interactions of two identical two-dimensional inviscid vortex pairs are investigated numerically by using the vortex sound theory and the method of contour dynamics. The sound sources are identified and then separated into two independent components, which represent the contributions from the vortex centroid dynamics and the microscopic vortex core dynamics. Results show that the sound generation mechanism of the latter is independent of the type

of vortex pair interaction, while that of the former depends on the jerks, accelerations, and vortex forces on the vortex pairs. The power developed by the vortex forces is found to be important in the generation of sound when the vortex cores are severely deformed and their centroids are close to each other. The isolated source terms also explain the appearance of wavy oscillations on the time variations of the sound source strengths in the vortex ring and the two-dimensional vortex interaction systems.

Tang, S. K. and Ko, N. W. M.

"BASIC SOUND GENERATION MECHANISMS IN INVISCID VORTEX INTERACTIONS AT LOW MACH NUMBER"

Journal of Sound and Vibration, Vol. 262, Issue 1, April 2003, pp. 87-115

The sound generation mechanisms during finite core vortex interactions at low Mach number are investigated in the present study. The theoretical deductions show clearly that the basic sound generation mechanisms are associated with the vortex core deformation and the vorticity centroid dynamics, independent of the vortex system. Such deductions are substantiated by numerical experiments with the interactions of two-dimensional vortices, vortex pairs and vortex rings. Detailed discussions on the similarities and differences between the sound generation processes of the two-dimensional and axisymmetric vortex systems are given. The relative importance of the two sound generation mechanisms in these vortex systems, their characteristics, and interactions, which are hardly found in existing literature, are also examined. The present findings have also generalized and substantiated the previous results of the authors on the topic.

Tang, S. K. and Ko, N. W. M.

"ON SOUND GENERATED FROM THE INTERACTION OF TWO INVISCID COAXIAL VORTEX RINGS MOVING IN THE SAME DIRECTION"

Journal of Sound and Vibration, Vol. 187, Issue 2, October 1995, pp. 287-310

Sound generation due to the interaction between two inviscid coaxial vortex rings moving along a common axis in the same direction is investigated numerically by using the method of contour dynamics and the far field equations. The results show the occurrence of the slip-through process, incomplete slip-through, coalescence and partial coalescence. They also illustrate that the radial accelerations and the rate of change of the axial accelerations of the vorticity centroids of the vortex rings are important in the generation of sound during the interaction. The axial separation of the vorticity centroids of the vortex rings and the third time derivative of the vortex impulse are found to be important only in the case of partial coalescence. As the vortex ring interactions considered in the present study are found in axisymmetric jets, the present results suggest that the jerk and acceleration of flow structures may be related to the generation of jet noise at low Mach number.

Tang, S. K. and Ko, N. W. M.

"SOUND GENERATION BY A VORTEX RING COLLISION"

Journal of Acoustical Society of America, Vol. 98, No. 6, December 1995, pp. 3418-3427.

A collision between two vortex rings and its sound generation is studied numerically using the contour dynamics method. Results suggest that the radial acceleration and the rate of change of the axial acceleration of the vortex rings are the more important dynamic parameters for sound generation during the interaction. The former is important at or near the pass-through instant when the vortex rings are coplanar and are of unequal strength. The latter, being important in the sound generation during a head-on collision before the vortex ring cores are very close to each other, especially when the rings are thin, is also important in sound generation by an unequal strength vortex ring collision after the pass through when the vortex cores are separated by a distance so that the mutual induction strength does not result in significant change of the impulse of the stronger ring.

Tangler, J. L.

"VORTEX DIFFUSION AND DISSIPATION"

US Patent 4,046,336, September 1977

Vortex diffusion means for an aircraft having lift structure rooted therein that extends outboard to a structure tip from which a discrete tip vortex develops when said tip is propelled through the air. A sub-wing extends from the tip of the lift structure. Preferably, the sub-wing has its leading edge or upper lead surface tangent to the upper lead surface of the lift structure and a span axis parallel to the span axis of the lift structure. The sub-wing's chord is sized to equally divide the bound vorticity shed at the tip of the lift structure so that twin discrete vortices are generated. One discrete vortex forms along the streamwise edge of the lift structure's tip and the other forms along the streamwise edge of the sub-wing's tip. The distance between the two vortices is in the range of from 25 to 50% of the local chord of the lift structure.

Tangler, J. L.

"EXPERIMENTAL INVESTIGATION OF THE SUBWING TIP AND ITS VORTEX STRUCTURE"

NASA CR-3058, November 1978, Bell Helicopter Textron, Fort Worth, TX.

Vortex diffusion resulting from the interaction of twin vortices generated by a 'subwing' tip was experimentally investigated. The purpose of the investigation was to provide a better understanding of the subwing's vortex structure relative to a square tip for several angle of attack and yaw angles. This comparison included subwings of various chord size and airfoil thickness. Flow visualization, together with performance and wake measurements, provided a comparison between the square tip and subwing tips during both a semi-span wind-tunnel test and a small-scale rotor hover-stand test. Through these studies, the subwing chord to main chord ratio which generated twin vortices was found to be 0.20. When the tip shed circulation was divided into twin vortices, the maximum circumferential

velocity in each vortex was lowered relative to a comparable square tip. The influence of yawed flow on the operation of the subwing was not a significant factor for yaw angles corresponding to those that occur on a helicopter rotor blade during partial power descent. Comparisons of subwings having different airfoil thicknesses showed this parameter to be unimportant. No noticeable difference in performance between the subwing and square tip could be detected at medium rotor thrust coefficients.

Tank, W. G.

"WAKE DETECTION WITH A VHF CW BISTATIC RADAR"

AIAA Paper No. 1997-0061, Reno, NV, January 1997

A proof-of-concept field test to demonstrate airplane wake detection with a VHF radar is described. The radar used for the test is a 10 watt, cw bistatic radar that operates at a frequency of 148.4 MHz with a system sensitivity of -134 dBm. No attempt was made to optimize system hardware or signal processing for wake detection; the radar was simply used 'as is' for the demonstration tests. These were conducted at the National Oceanic and Atmospheric Administration (NOAA) Research Facility at Idaho Falls, Idaho. For them, the radar antennas were positioned, and elevation angles adjusted, such that the radar common volume -- the intersection of the 3dB transmit and receive antenna patterns -- was normal to and at the altitude of the flight track of a B727 airplane performing flybys past an instrument tower used to study wake wind speeds and internal structures. There were three definite and two probable wake detections out of a total of 15 flybys that offered the possibility for wake detection. Radar returns from wakes are due to backscattering as a coherent interaction between the radar signal and half-wavelength fluctuations in radio refractive index caused by turbulence inside the wake volume. The probability density of the magnitude of such fluctuations indicates that the one-in-three wake detection success rate at Idaho Falls was as expected, considering the 'as is' system sensitivity of the test radar. This now suggests an intriguing possibility. Every airport with Instrument Landing System (ILS) capabilities utilizes inner, middle, and outer VHF fan beam markers at increasing distance from runway thresholds, to assist approaching airplanes in maintaining the standard 3.5 deg. approach glide slope. These marker beacons could serve as the transmitters for bistatic radars to warn airplanes in the landing/takeoff cycle of residual wakes in airport approach zones.

Tank, W. G. and Stinson, W. E.

"THE DISSIPATIVE EFFECTS OF JET AIRCRAFT WAKES ON FOG"

Bulletin of the American Meteorological Society, Vol. 53, No. 11, November 1972, p. 115

An investigation was made of the imprint in fog of the landing approach of a Boeing 747 aircraft wake. It was found that the individual vortices increase in size downstream until they meet at the vertical plane of symmetry, at which point they interact, with annihilation gradually taking place. A typical observed lifetime of the visible wake is 2-5 min.

Tao, J. S., Huang, X. Y. and Chan, W. K.

"A FLOW VISUALIZATION STUDY ON FEEDBACK CONTROL OF VORTEX SHEDDING FROM A CIRCULAR CYLINDER"

J. Fluids and Structures, Vol. 10, Issue 8, Nov. 1996, pp. 965-970

This note presents flow visualization results to show the response of wake flows behind a cylinder to the feedback suppression and excitation. The experiments were conducted in a water channel and the feedback perturbations were introduced into the wake by oscillating the cylinder transverse to the oncoming flow. The visualization photographs directly illustrated the wake flows under the feedback suppression and excitation at Reynolds numbers up to 25 percent above the natural onset Reynolds number for vortex shedding.

Tardif, R. and Zwack, P.

"PROVIDING METEOROLOGICAL SUPPORT TO THE AIRCRAFT VORTEX SPACING SYSTEM USING THE COBEL ONE-DIMENSIONAL MODEL"

Project Report, September 1998, University of Quebec, Montreal, Canada.

Efforts are currently underway to develop the Aircraft Vortex Spacing System to dynamically determine the required aircraft spacing in the approach zone of busy airports according to aircraft type and meteorological conditions. The role of an important sub-system of the AVOSS is to provide timely and accurate meteorological input to wake vortex transport/decay algorithms. A coupled 3D/1D numerical prediction system is proposed. An operational 3D mesoscale model is used to provide input to a high-resolution boundary layer model to produce detailed forecasts of the lower atmospheric vertical structure. The COBEL column model, developed in France at the Paul Sabatier University, is used for that purpose. A real-time version of the system, incorporating data assimilation capabilities, was developed and tested during the AVOSS field deployment at the Dallas-Fort Worth airport in the fall of 1997. Preliminary results from the deployment show that high-resolution diagnosed and predicted profiles of boundary layer temperature and wind agree well with the available observations. Computed values of turbulence kinetic energy also agree well with the observations during the night, but COBEL seem to provide values that are too large during sunny days. This issue remains to be investigated further. Refinement of the data assimilation method currently implemented in the column model is also recommended.

Targ, R., Hawley, J. G., Steakley, B. C., Ames, L. L. and Robinson, P.

"AIRBORNE LIDAR WIND DETECTION AT 2 MICRONS"

Proceedings SPIE, Vol. 2464, Air Traffic Control Technologies, June 1995, pp. 109-115.

NASA and the FAA have expressed interest in laser radar's capabilities to detect wind profiles at altitude. Several programs have been addressing the technical feasibility and utility of laser radar atmospheric backscatter data to determine wind profiles and wind hazards for aircraft guidance and

navigation. In addition, the U.S. Air Force is investigating the use of airborne lidar to achieve precision air drop capability, and to increase the accuracy of the AC-130 gunship and the B-52 bomber by measuring the wind field from the aircraft to the ground. There are emerging capabilities of airborne laser radar to measure wind velocities and detect turbulence and other atmospheric disturbances out in front of an aircraft in real time. The measurement of these parameters can significantly increase fuel efficiency, flight safety, airframe lifetime, and terminal area capacity for new and existing aircraft. This is achieved through wind velocity detection, turbulence avoidance, active control utilization to alleviate gust loading, and detection of wingtip wake vortices produced by landing aircraft. This paper presents the first flight test results of an all solid-state 2-micron laser radar system measuring the wind field profile 1 to 2 km in front of an aircraft in real time. We find 0.7-m/s wind measurement accuracy for the system which is configured in a rugged, light weight, high-performance ARINC package.

Targ, R., Kavaya, M. J., Huffaker, R. M. and Bowles, R. L.

"COHERENT LIDAR AIRBORNE WINDSHEAR SENSOR: PERFORMANCE EVALUATION"

Applied Optics, Vol. 30, No. 15, May 1991, pp. 2013-2026.

National attention has focused on the critical problem of detecting and avoiding windshear since the crash on 2 Aug. 1985 of a Lockheed L-1011 at Dallas/Fort Worth International Airport. As part of the NASA/FAA National Integrated Windshear Program, we have defined a measurable windshear hazard index that can be remotely sensed from an aircraft, to give the pilot information about the wind conditions he will experience at some later time if he continues along the present flight path. A technology analysis and end-to-end performance simulation measuring signal-to-noise ratios and resulting wind velocity errors for competing coherent laser radar (lidar) systems have been carried out. The results show that a Ho:YAG lidar at a wavelength of 2.1 microns and a CO₂ lidar at 10.6 microns can give the pilot information about the line-of-sight component of a windshear threat from his present position to a region extending 2-4 km in front of the aircraft. This constitutes a warning time of 20-40 s, even in conditions of moderately heavy precipitation. Using these results, a Coherent Lidar Airborne Shear Sensor (CLASS) that uses a Q-switched CO₂ laser at 10.6 microns is being designed and developed for flight evaluation in the fall of 1991.

Tartaglione, J. J.

"AN ANALYSIS OF THE AIRCRAFT TRAILING VORTEX SYSTEM"

AIAA Paper No. 1978-0312, Washington, DC, February 1978

A review of the aircraft trailing vortex system is presented. Particularly the transport and decay of the vortex systems and its potential hazard to other aircraft is discussed. In addition, an analysis of trailing vortex decay data is presented. Although various theories have been proposed for predicting the decay of a vortex system, most of them have failed when compared with flight test data. Recently J. D. Iversen proposed a method for correlating trailing vortex data based upon a variable eddy viscosity vortex decay model. His model was applied to previously uncorrelated flight test data. The data used,

which was obtained by the National Aviation Facilities Experimental Center (NAFEC), includes measurements of the vortex structure behind nearly all the large commercial jet transports. The correlation technique was found to successfully collapse the trailing vortex data to a single curve. Thus, Iversen's assumption of variable eddy viscosity is the key factor that enables a universal collapse of both the model and flight test data.

Tatnall, C. R.

"A PROPOSED METHODOLOGY FOR DETERMINING WAKE-VORTEX IMPOSED AIRCRAFT SEPARATION CONSTRAINTS"

M.S. Thesis, August 1995, George Washington Univ., Washington, DC.

The main objective of this thesis is to develop a rational approach to determining the aircraft spacings required to comply with a prescribed limit on the amount of roll-upset due to wake-vortex interactions. This is done by analytically modeling the vortex-induced flow field, and using a theoretical approach to obtain expressions for the vortex-induced lift and roll moment on a following aircraft. Transient dynamic models are developed to determine the maximum potential vortex-induced roll upset, employing a derived conservative vortex decay law. The models are applied in order to find time-separations required for each aircraft pair in a given representative aircraft population, so that a prescribed upset limit is not exceeded. Next, a method for quantifying the total system capacity loss (lost time) due to partitioning the aircraft into classes and assigning conservative spacings for the class-pair combinations is derived, so that the class-based spacing system which maximizes airport capacity can be determined.

Tatnall, C. R.

"AN INVESTIGATION OF CANDIDATE SENSOR-OBSERVABLE WAKE VORTEX STRENGTH PARAMETERS FOR THE NASA AIRCRAFT VORTEX SPACING SYSTEM (AVOSS)"

NASA CR-1998-206933, March 1998, George Washington University, Joint Institute for Advancement of Flight Sciences, Hampton, VA

The counter-rotating pair of wake vortices shed by flying aircraft can pose a threat to ensuing aircraft, particularly on landing approach. To allow adequate time for the vortices to disperse/decay, landing aircraft are required to maintain certain fixed separation distances. The Aircraft Vortex Spacing System (AVOSS), under development at NASA, is designed to prescribe safe aircraft landing approach separation distances appropriate to the ambient weather conditions. A key component of the AVOSS is a ground sensor, to ensure safety by making wake observations to verify predicted behavior. This task requires knowledge of a flowfield strength metric which gauges the severity of disturbance an encountering aircraft could potentially experience. Several proposed strength metric concepts are defined and evaluated for various combinations of metric parameters and sensor line-of-sight elevation angles. Representative populations of generating and following aircraft types are selected, and their associated wake flowfields are modeled using various wake geometry definitions. Strength metric

candidates are then rated and compared based on the correspondence of their computed values to associated aircraft response values, using basic statistical analyses.

Tauszig, L.

"NUMERICAL DETECTION AND CHARACTERIZATION OF BLADE VORTEX INTERACTIONS USING FREE WAKE ANALYSIS"

M.S. Thesis, August 1998, Pennsylvania State University, Philadelphia, PA

A free wake methodology has been implemented to predict the location of the tip vortices released by a helicopter rotor. In conjunction with the free wake model, a method to detect Blade Vortex Interaction (BVI) - called the spherical detection criteria - has been developed. From the geometry of the wake and the location of the blade, this criterion detects the occurrence of BVI and allows a detailed characterization of the interaction, including parameters such as angle of interaction and wake age. Validation of the free wake methodology has been achieved through comparison of time-averaged inflow and wake geometry with experimental data. The predicted blade vortex interactions have also been validated against acoustical measurements. The current methodology correlates well with experimental data and captures the trend of the change in BVI location as shaft angle and advance ratio are changed. The implementation of this model is computationally efficient and will be valuable to the study of both passive and active rotor designs for alleviation of blade vortex interaction.

Tavella, D. A., Wood, N. J., Lee, C. S. and Roberts, L.

"LIFT MODULATION WITH LATERAL WING-TIP BLOWING"

J. Aircraft, Vol. 25, No. 4, April 1988, pp. 311-316

The utilization of a thin jet of air exiting in the spanwise direction from a slot at each of the tips of a straight wing has been investigated as a means of generating weak lift modulation. A theory showing the analytical relationship between blowing intensity and aerodynamic forces was developed and its results were compared against experiments. It was found that the lift gain due to lateral blowing depends on the $2/3$ power of the jet blowing intensity.

Taylor, L. W. and McLaughlin, M. D.

"A MODIFIED NEWTON-RAPHSON ANALYSIS OF FLIGHT MEASUREMENTS OF THE TRAILING VORTICES OF A HEAVY JET TRANSPORT"

NASA TN D-7404, August 1974, NASA Langley Research Center, Langley Station, VA

A modified Newton-Raphson method has been used to determine the parameters in equations describing the vortex flow to obtain a best match with flight measurements of the flow behind the C-5A airplane. The flight measurements were made using a specially instrumented T-33 airplane which passed as closely as possible to the centers of the trailing vortices at several distances behind the C-5A

airplane. The flight measurements were transformed to flow velocity relative to an inertial frame of reference. The assumed form of the flow consisted of the superposition of two counterrotating, finite core vortices. The positions of the vortex centers, their total circulation, the effective eddy viscosity and measurement bias were the parameters adjusted. Previous analyses of the experimental data have used graphical techniques to determine vortex-flow parameters. The modified Newton-Raphson method of analysis eliminates considerable manual labor and yields more consistent vortex-flow parameters.

Taylor, R. M.

"AERODYNAMIC SURFACE TIP VORTEX ATTENUATION SYSTEM"

US Patent 5,158,251, October 1992.

Apparatus and method for attenuating fluid foil tip vortices, featuring a 'Coanda tip' and a 'Coanda curtain.' The fluid foil tip has a Coanda surface and means for discharging compressed fluid adjacent thereto; a resultant fluid barrier is formed generally chordwise and perpendicular to the fluid foil plane and tangential to the fluid foil tip upon Coanda entrainment and deflection of the discharged compressed fluid. The fluid barrier prevents crossflow from the higher-pressure fluid region to the lower pressure fluid region, the fluid regions being separated by the fluid foil when moving relatively through a fluid, the fluid barrier thereby stemming tip vortex generation at its source.

Teager, S. A., Biehl, K. J., Garodz, L. J., Tymczyszyn, J. J. and Burnham, D. C.

"FLIGHT TEST INVESTIGATION OF ROTORCRAFT WAKE VORTICES IN FORWARD FLIGHT"

DOT/FAA/CT-94/117, February 1996, FAA Technical Center, Atlantic City Airport, NJ

This report presents the results of helicopter flight tests and wake vortex measurements which were designed to provide data necessary for the assessment of hazards to following aircraft. The tests described in this report were conducted using small probe airplanes and a Laser Doppler Velocimeter for wake vortex measurements during forward-flight helicopter operations. Four helicopters, having weights ranging from 7,600 to 70,000 pounds, were used in the tests as the wake vortex generating aircraft. Wake vortex strength and decay characteristics as determined from the flight test results are discussed. In the absence of encounter measurements for the case of hover flight, it is recommended that small airplanes, at the same altitude and downwind of a hovering helicopter, maintain at least 500 feet of separation.

Tee, Y. Y. and Zhong, Z. W.

"MODELLING AND SIMULATION STUDIES OF THE RUNWAY CAPACITY OF CHANGI AIRPORT"

The Aeronautical Journal, Vol. 122, No. 1253, July 2018, pp, 1022-1037.

International air travel becomes more affordable over the years with the introduction of low-cost carriers (LCCs) in Asia Pacific. As a result, this region has seen an exponential growth in its air traffic movements. Asia Pacific has been recording faster air traffic growths, compared to regions such as Europe and North America. This is largely due to emerging markets and developing economies in Asia Pacific. This is especially seen in the demand and supply for LCCs in Southeast Asia. Changi Airport, being one of the major air traffic hubs in Asia, is facing overloaded traffic in the future due to this exponential growth. Although a new runway and new terminals are proposed and in the process of being built, the coming years could still bring a huge challenge to the airport, if its existing capacity is not maximized to cope with the increasing traffic demand. Hence, we studied the impacts of increasing LCC flights on the airport runway capacity. Different runway operational scenarios were simulated to investigate their advantages and disadvantages. It is found that the segregated parallel arrival-departure runway operation is beneficial. By simulating various operational scenarios with the projected increasing flight movements, it is found that a dedicated runway to medium-sized arrival aircraft may be more beneficial, as this would possibly enable it to have a higher runway capacity.

Tendero, J. A., Paredes, P., Roura, M., Govindarajan, R. and Theofilis, V.

"BIGLOBAL AND POINT VORTEX METHODS FOR THE INSTABILITY ANALYSIS OF WAKES"

AIAA Paper 2013-2820, June 2013, San Diego, CA.

To better understand destruction mechanisms of wake-vortices behind aircraft, the point vortex method for stability (inviscid) used by Crow is here compared with viscous model global stability analysis of the linearized Navier-Stokes equations acting on a two-dimensional basic flow, i.e. BiGlobal stability analysis. The fact that the BiGlobal method is viscous, and uses a finite area vortex model, gives rise to results somewhat different from the point vortex model. It adds more parameters to the problem, but is more realistic.

Tendero, J. A., Theofilis, V., Roura, M. and Govindarajan, R.

"ON VORTEX FILAMENT METHODS FOR LINEAR INSTABILITY ANALYSIS OF AIRCRAFT WAKES"

Aerospace Science and Technology, Vol. 44, 2015, pp. 51-68.

Linear stability analysis of vortical systems is discussed in a systematic manner using the classic inviscid vortex filament method. Well-known results are recovered as special cases of a unified linearization procedure. The symmetries of the vortex systems analyzed are exploited to obtain an analytical picture of different classes of growing and decaying eigenmodes. Finally, comparisons with viscous global linear theory reveal the limits of applicability of the vortex filament method for the instability analysis of realistic vortex systems.

Teo, R. and Tomlin, C. J.

"COMPUTING PROVABLY SAFE AIRCRAFT TO AIRCRAFT SPACING FOR CLOSELY SPACED PARALLEL APPROACHES"

Proceedings of the Digital Avionics Systems Conference, Philadelphia, PA, October 2000

One of the requirements for closely spaced parallel approaches (CSPA) is the proof that possible blunders of the adjacent aircraft do not lead to a loss of separation. Our paper addresses this problem by considering the blunderer as a 'pursuer' and the other aircraft as an 'evader'. We then use differential game methodology to find the safe region in which it is guaranteed that blunders do not lead to a loss of separation. We apply the technique to a practical case to show how the minimum safe longitudinal separation (MSLS) can be computed. Finally, simulation is performed to show how the technique can be used as an alerting algorithm for onboard on-line computation.

Teo, R. and Tomlin, C. J.

"COMPUTING DANGER ZONES FOR PROVABLY SAFE CLOSELY SPACED PARALLEL APPROACHES"

Journal of Guidance, Control, and Dynamics, Vol. 26, No. 3, May-June 2003, pp. 434-442.

The use of a differential game and an optimal control theoretic approach for computing danger zones for this problem is new. The space outside the danger zone is deemed provably safe, implying that during blunder situations emergency evasive maneuvers starting from outside the zone are guaranteed to be safe within limits on the maneuver severity of both the blundering and evading aircraft. In addition, these zones can be computed online in real time with knowledge of the current state. The algorithm also provides the minimum runway spacings for independent approaches and the minimum longitudinal separation between aircraft for dependent approaches. The algorithm for computing the zones has been validated with over one million simulation runs, where the adjacent aircraft performed various blunder trajectories. The validation shows that the algorithm could successfully alert and prevent collisions in 100 percent of the simulations run.

Teo, R., Jang, J. S. and Tomlin, C. J.

"FLIGHT DEMONSTRATION OF PROVABLY SAFE CLOSELY SPACED PARALLEL APPROACHES"

AIAA Paper 2005-6197, August 2005, San Francisco, CA.

In poor visibility, paired approaches to airports with closely spaced parallel runways are not permitted, thus halving the arrival rate. With Global Positioning System technology, datalinks, and cockpit displays, this could be averted. One important problem is ensuring safety during a blundered approach by one aircraft. This is on-going research. A danger zone around the blunderer is required. If the correct danger zone could be calculated, then it would be possible to get 100 percent of clear-day capacity in poor-visibility days even on 750-foot runways. The danger zones vary significantly (during an approach) and calculating them in real time would be very significant. Approximations (e.g. outer bounds) are not good enough. This paper presents a way to calculate these danger zones in real time for a very broad class of blunder trajectories. The approach in this paper differs from others in that it

guarantees safety for any possible blunder trajectory if the speeds and turn rates of the blunder are within certain bounds. In addition, the approach considers all emergency evasive maneuvers whose speeds and turn rates are within certain bounds about a nominal emergency evasive maneuver. For all combinations of these blunder and evasive maneuver trajectories, it guarantees that the evasive maneuver is safe. For more than 1 million simulation runs, the algorithm shows a 100 percent rate of Successful Alerts and a 0 percent rate of Collisions Given an Alert. The evaluation of the proposed scheme was demonstrated with two different types of test platforms, the Stanford DragonFly unmanned aerial vehicles and the Boeing testbed of F-15 and T-33 aircraft. The experiment involved two aircraft, where one aircraft is assigned as pursuer and the other as evader. The algorithm proved the guaranteed safety (maintaining a minimum separation distance) for every single flight test performed, and demonstrated that it can run it in real-time.

Teske, M. E.

"COMPUTER PROGRAM FOR PREDICTION OF THE DEPOSITION OF MATERIAL RELEASED FROM FIXED AND ROTARY WING AIRCRAFT"

NASA CR-3780, March 1984, Continuum Dynamics, Princeton, NJ

This is a user manual for the computer code 'AGDISP' (AGricultural DISPersal) which has been developed to predict the deposition of material released from fixed and rotary wing aircraft in a single-pass, computationally efficient manner. The formulation of the code is novel in that the mean particle trajectory and the variance about the mean resulting from turbulent fluid fluctuations are simultaneously predicted. The code presently includes the capability of assessing the influence of neutral atmospheric conditions, inviscid wake vortices, particle evaporation, plant canopy and terrain on the deposition pattern.

Teske, M. E. and Thistle, H. W.

"ATMOSPHERIC STABILITY EFFECTS IN AIRCRAFT NEAR-WAKE MODELING"

AIAA Journal, Vol. 40, No. 7, 2002, pp. 1467-1469

The note illustrates that atmospheric stability effects in the aircraft near-wake can be simulated using the UNIWAKE code. The vortex decay rates under various atmospheric stability conditions computed from UNIWAKE are then integrated into AGDISP and AgDRIFT codes, developed by the Departments of Agriculture Forest Service and the Environmental Protection Agency, for studying dispersion of sprays behind aircraft.

Teske, M. E. and Thistle, H. W.

"RELEASE HEIGHT AND FAR-FIELD LIMITS OF LAGRANGIAN AERIAL SPRAY MODELS"

Transactions of the ASAE, Vol. 46 (4), 2003, pp. 977-983.

The Lagrangian equation solver in the aerial application models AGDISP (version 8.08) and AgDRIFT (version 2.0.08) can predict deposition from high release heights and to distances far downwind, beyond where these models have been validated. The appropriateness and applicability of model extension to higher release heights and to farther downwind distances are examined by examining model inputs, model uncertainty, and data variability as these limits are approached. The models appear appropriate if the aircraft vortices influence the behavior of the released spray material. While the models have been validated to release heights of 10 m and downwind distances of 800 m, release height extension appears warranted, whereas downwind deposition extension does not. However, relative deposition effects may be examined further downwind.

Teske, M. E. and Thistle, H. W.

"A SIMULATION OF RELEASE HEIGHT AND WIND SPEED EFFECTS FOR DRIFT MINIMIZATION"

Transactions of the ASAE, Vol. 42 (3), 1999, pp. 583-591.

The near-wake portion of the USDA Forest Service aerial application prediction model FSCBG is applied to a sensitivity study of the length of the spray boom relative to the length of the aircraft wingspan or helicopter rotor diameter. Building on extensive previous work, this study examines the predictions by the near-wake Lagrangian trajectory model of swath width, mean deposition within the spray block, and drift fraction downwind of the edge of the field. Ten aircraft and four BCPC droplet size distributions are used to simulate a typical agricultural application scenario. Findings from this study demonstrate the effects of varying boom length on downwind drift, the reduction of downwind drift with larger droplets, and the inherent ability of certain aircraft type to reduce downwind drift more easily than others. Model results indicate that a broad range of boom length (between 60 and 100% of aircraft wingspan or helicopter rotor diameter) recovers approximately the same levels of downwind drift, decreasing levels of mean deposition within the spray block, and increasing swath width between flight lines. The suggestion that boom length should be less than 75% of wingspan or rotor diameter is perhaps based more on the anticipated position of the rolled-up vortices than on solid experimental evidence.

Teske, M. E., Bilanin, A. J. and Barry, J. W.

"DECAY OF AIRCRAFT VORTICES NEAR THE GROUND"

AIAA Journal, Vol. 31, No. 8, August 1993, pp. 1531-1533

Between 1985 and 1991, a series of aircraft flybys above tower grids instrumented with propeller anemometers produced a large data base on vortex motion near the ground. Anemometer tower grids recorded the ambient vertical time histories as various aircraft repeatedly traversed normal to the grid. These digitized velocity traces produced an aircraft wake signature that could be used to infer the strength and lateral and vertical motion of the aircraft vortex pairs generating the traces. A vortex decay coefficient as a function of initial vortex circulation strength, ambient turbulence level, and aircraft semispan was obtained.

Teske, M. E., Birchfield, N. B. and Bird, S. L.

"DEVELOPMENT AND VALIDATION OF A MECHANISTIC GROUND SPRAYER MODEL"

ASAE/CSAE Paper No. 040136, Ottawa, Canada, August 2004

This paper summarizes the development of a mechanistic ground sprayer model, built upon the same analytical Lagrangian approach used in the aerial spray model AGDISP. For the ground sprayer model the wake and turbulence of the aircraft are removed and more detailed modeling of the nozzle jets (and jet entrainment) are included. The ground model predicts the spray deposition downwind from the application area for any set of initial conditions, and recovers results consistent with Spray Drift Task Force field data.

Teske, M. E., Kaufman, A. E., George, C. W. and Johnson, G. M.

"FIELD MEASUREMENTS OF HELICOPTER ROTOR WASH IN HOVER AND FORWARD FLIGHT"

J. Aircraft, Vol. 34, No. 6, November-December 1997, pp. 813-814

Up to now, the effect of a passing helicopter on the local meteorology, particularly near a forest fire, has been understood only from a qualitative standpoint. Because the quantitative data are considered important in understanding fire propagation and the dispersal of pesticides and other contaminants, a cooperative field study was recently conducted to collect such data, with the hope that these data may be used to validate models of helicopter wakes, suggest operational methods for fighting forest fires, and provide insight into the dispersal of dusts, aerosols, and other contaminants in the atmosphere.

Teske, M. E., Quackenbush, T. R., Bilanin, A. J. and Wachspress, D. A.

"VORTEX ROLL-UP, MERGING AND DECAY WITH THE UNIWAKE COMPUTER PROGRAM"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 33-1 - 33-2.

The numerical simulation of vortex merging and decay, particularly behind large commercial aircraft, was initially made possible by the NASA WAKE code developed in 1975. Significant enhancements to that code were achieved in the last three years with the development of the UNIWAKE code for the Department of Transportation. This code combines four elements of the merging process: (1) a vortex lattice model patterned after the work of Margason and Lamar to determine the wing loading; (2) a Betz roll-up model of the load distribution, including axial velocity effects; (3) a turbulent transport finite difference model extending the previous WAKE solution scheme to fourth-order accuracy; and (4) a three-dimensional unsteady analysis replacing the merged vortices by curved vortex elements, leading to vortex linking and pinch-off. This paper summarizes each model stage, and examines extensions for solution improvement.

Teske, M. E., Quackenbush, T. R., Sykes, R. I. and Bilanin, A. J.

"LONG-TIME AIRCRAFT VORTEX WAKE PREDICTIONS AND PLUME EVOLUTION CONSEQUENCES"

AIAA Paper No. 1997-1843, Snowmass Village, CO, June 1997

This paper summarizes ongoing work on the prediction of wake/exhaust mixing for subsonic aircraft, with particular emphasis on long-time wake effects. The primary objective of this work addresses the need for a continuous model prediction of the wake of a subsonic aircraft (from the trailing edge of the wing to times late downstream), its entrainment of engine products, and the consequences of the chemistry of these products on the atmosphere; in particular, the process of exhaust mixing, dispersion and chemical reactions in the upper atmosphere, and the assessment of atmospheric effects of commercial aviation. The modeling described here brings together two validated computer models: UNIWAKE, a near-wake model for vortex roll-up and entrainment, and SCIPUFF, a widely used atmospheric plume dispersion model. The coupled model tracks gas-phase species, temperature and velocity fields, and passive tracers in the presence of realistic wind fields, over periods of 24 hours or more after initiation of the wake trail.

Teske, M. E., Thistle, H. W. and Ice, G. G.

"TECHNICAL ADVANCES IN MODELING AERIALY APPLIED SPRAYS"

Transactions of the ASAE, Vol. 46 (4), 2003, pp. 985-996

Since the 1989 publication of the original modeling approaches assembled into AGDISP, significant advances have been made in the development and validation of spray drift models. The latest version of AGDISP (version 8.08) now embodies the latest refinements to the computational engine first developed for NASA, improved by the USDA Forest Service, and implemented by the Spray Drift Task Force and the U.S. Environmental Protection Agency into a regulatory version. This article updates the previous summary of AGDISP, builds on a recent publication summarizing the regulatory version of the model, and includes the most recent modeling additions of atmospheric stability effects, vortical decay, simple terrain features, plant canopy, riparian barriers, and the aerial release of dry materials.

Teske, M. E., Thistle, H. W., Latham, M. and Reynolds, W. H.

"APPLICATION OPTIMIZATION FOR MOSQUITO VECTOR CONTROL"

ASAE/CSAE Paper No. 044201, Ottawa, Ontario, Canada, August 2004

This paper explores the behavior of aircraft vortices in an early-morning environment. Model calculations are run to the point of complete vortical decay, at which time the downwind and vertical incremental distances from the point of release are obtained. In this way, sensitivity to atmospheric stability, crosswind, evaporation, drop size distribution, and aircraft type may be explored. The relative displacement of the spray material may then be used to estimate where to release the spray material in order to reach a specified target several kilometers downwind.

Teske, M. E., Valcore, D. L. and Hewitt, A. J.

"AN ANALYTICAL GROUND SPRAYER MODEL"

ASAE Paper No. 01-1051, Sacramento, CA, July 30-August 1, 2001

This paper summarizes an analytical ground sprayer model developed with the same Lagrangian approach used in AGDISP and AgDRIFT, and validated with field data collected by the Spray Drift Task Force. The model predicts the deposition downwind from the application area for any set of initial conditions, and recovers results consistent with those obtained for aerial application by the aerial model.

Teske, M. E., Wachspress, D. A. and Thistle, H. W.

"PREDICTION OF AERIAL SPRAY RELEASE FROM UAVS"

Transactions of the American Society of Agricultural and Biological Engineers, Vol. 61, No. 3, 2018, pp. 909-918.

This article summarizes the ability of CHARM+AGDISP to predict the drift and deposition of sprays released from rotary wing unmanned aerial vehicles (UAVs). This predictive capability results from merging algorithms for spray transport, as found in AGDISP (AGricultural DISPersal), with CHARM (Comprehensive Hierarchical Aeromechanics Rotorcraft Model). The resulting software tracks the release of spray droplets from nozzles on the UAV to deposition on the ground. To date, both AGDISP and CHARM, a code that provides a complete representation of the time-varying, unsteady flow field surrounding a helicopter during transient maneuvering flight near the ground, have been extensively validated. The CHARM+AGDISP software is applied to two UAVs to explore the flow field regimes that present challenges for effective UAV operations. The simulations undertaken indicate flight conditions that yield acceptable deposition levels and minimize drift; inversely, conditions are also identified that result in off-target drift that may be problematic.

Tetzlaff, G., Franke, J. and Schilling, V.

"WAKE VORTEX PROPAGATION IN THE ATMOSPHERIC BOUNDARY LAYER"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 47-1 - 47-19

The Rhein-Main Airport in Frankfurt, Germany, has two parallel runways separated by 518 m. This distance is not sufficient to operate the runways independently. To achieve a part time independent operation for Frankfurt a three-phase program was designed. In a first phase wind sensors were deployed to simply answer the question whether wake vortices are capable to travel across to the other runway in critical strength. The second phase tries to define the weather situations and their operational handling during which an independent operation would be within regulations. The

methods employed in this phase do not solely rely on the experimental findings but also include the results of numerical simulations of the vortex propagation at the surface. The third phase will incorporate the findings of the first two phases in the actual running of the airport. This will happen stepwise and carefully scaled in close contact with all involved parties.

Theisen, J. G.

"VORTEX FLOWS IN WAKES"

Proceedings of Boundary Layer Symposium, ER-8290, Lockheed-Georgia Research Lab., 1965, pp. 151-178

A steady solution of the viscous Navier-Stokes equations for a vortex flow field has been obtained. A perturbation form of the circulatory terms leads to a nonlinear, total differential equation having a solution characterized by spatially periodic waveforms, including nonlinear harmonics as multiples of the fundamental. The existence of aperiodic spatial waveforms is shown to be dependent upon an hypothesized form of the axial stream function used in a variable-separable solution. The perturbation transformation and the omission of explicit time-dependency result in a formulation which is not useful for evaluating the magnitudes of the circulation and stream function. Rather, they permit a study of quasi-periodic waveforms in the stream function for a vortex flow.

Theisen, J. G.

"VORTEX PERIODICITY IN WAKES"

AIAA Paper No. 1967-0034, New York, NY, January 1967

An analytic solution is presented for the Navier-Stokes equations associated with vortex flows, including nonlinear, viscous terms. Appropriate consideration of three-dimensional disturbances, recently observed experimentally in wakes has enabled reduction of these equations to tractable form using perturbation analysis. Both stable and unstable, peripherally periodic modes for a vortex with large swirl (small Rossby number) are determined for radial and tangential velocities as functions of the radial inflow Reynolds number and the Rossby number.

Theisen, J. G.

"V/STOL STABILITY AND CONTROL IN TURBULENCE"

Proceedings of the National Aerospace Meteorology Conference, AMS/AIAA, 1968, pp. 505-514

The six-degree-of-freedom equations of motion employed in early simulations of wake penetration dynamics are described. Both digital and analog computers were employed with a fixed base simulator, useful for basic stability and trend studies.

Theisen, J. G. and Scruggs, R. M.

"VISCID EFFECTS ON WAKE TURBULENCE PERSISTENCE AND STABILITY"

Proceedings of the Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorological Society, 1974, pp. 370-377

A mathematical analysis is given which describes the basic features of the process of the generation of an axial periodicity in vortices which are being fed non-conservatively by the shear layers of an external flow in a non-axisymmetric manner. The existence of atmospheric wind-shear mechanisms provides a broad-band, periodic feeding of vorticity along the axis of a vortex contrail, so that the source of energy to amplify a resonant excitation such as vortex burst is apparent. Also, differential flap motion could excite the non-axis-symmetric modes observed.

Theisen, J. G. and Scruggs, R. M.

"AIRCRAFT WAKE VORTEX DYNAMIC STABILITY SUBJECTED TO REAL ATMOSPHERIC EFFECTS"

LG75-ER0125, June 1975, Lockheed-Georgia, Marietta, GA

Three-dimensional turbulence theory is used with a vortex filament model of aircraft contrails to predict the probability that the theoretical core-wise wavelengths can be amplified to cause a 'breakdown' of the primary axisymmetric vortex. Such a cascading of energy is ideally sought as a possible solution of the vortex wake hazard problem.

Theisen, J. G., Scruggs, R. M. and Dixon, C. J.

"VORTEX WAKE OPERATING PROBLEMS, ANALYSIS AND TESTING"

LG73-ER-0021, August 1973, Lockheed-Georgia Company, Marietta, G.

A mathematical analysis is given which describes the features of the process of the generation of an axial periodicity in vortices which are being fed non-conservatively by the shear layers of an external flow in a non-axisymmetric manner. A vortex-lattice computer simulation is described of a tip-mounted nacelle with power effects on the wing vortex wake. Canted end-plates were also simulated, and the effects on span-lift distribution were similar, to first order, compared with the nacelle mounted cases.

Theodore, C. and Celi, R.

"HELICOPTER FLIGHT DYNAMIC SIMULATION WITH REFINED AERODYNAMICS AND FLEXIBLE BLADE MODELING"

Journal of Aircraft, Vol. 39, No. 4, July-August 2002, pp. 577-586.

A coupled rotor-fuselage flight dynamic model that includes a maneuvering free wake model and a coupled flap-lag-torsion flexible blade model, as well as the results of an investigation on some effects

of inflow and blade modeling on the free-flight response of a hingeless rotor helicopter to pilot inputs, are described. The wake model is a relaxation type free wake, capable of modeling the wake geometry changes due to maneuvers; no assumptions are made on the wake geometry, which is free to evolve based on the maneuver. Theoretical predictions are compared with flight-test data. The results show that the free-flight, on-axis response to pilot pitch and roll inputs can be predicted with good accuracy with a relatively unsophisticated model. It is possible to predict the off-axis response from first principles, that is, without empirically derived correction factors and without assumptions on the wake geometry. To do so, however, requires sophisticated modeling. Both a free wake model that includes the wake distortions caused by the maneuver and a refined flexible blade model must be used. Most features of the off-axis response can be captured using a dynamic inflow theory extended to account for maneuver-induced wake distortions, for a fraction of the cost of using a free wake model. The most cost-effective strategy, for typical flight dynamic analyses and if vibratory loads are not required, is probably to calibrate such a theory using the more accurate free-wake based model, and then use it in all calculations.

Thistle, H. W., Teske, M. E. and Richardson, B.

"SPRAY DROPLET TRAJECTORY LENGTH IN AMBIENT VORTICES"

ASAE/CSAE Paper No. 041088, Ottawa, Ontario, Canada, August 2004

The length of droplet trajectories is important in applied deposition modelling of aerial sprays. The length of the trajectory determines the time over which evaporation will act on a droplet as well as the likelihood a droplet will encounter a canopy element. In this paper vortical motion in the atmosphere is parameterized by analyzing time series of wind speed data. Resultant discrete vortices are then defined and fit to a Lamb Vortex. Individual droplets are numerically dropped into the vortices and trajectory pathlength calculated. Trajectories of 50 drops are nearly circular while 350 drops are only slightly deflected by the lowest energy vortex analyzed here.

Thobois, L. and Cariou, J. P.

"IMPROVING THE MITIGATION OF WIND HAZARDS IN ATM OPERATIONS WITH GROUND-BASED WIND DOPPLER LIDARS"

Fifth SESAR Innovation Days, December 2015, Bologna, Italy.

Weather is one of the major causes of flight delays and accidents. Among all the weather conditions for aircrafts, wind and wind hazards like wake vortices and wind shears require to be monitored with high spatial and temporal resolution sensors to reduce their impact on air traffic for improving safety and/or for optimizing ATM. Among the different available sensor technologies, Doppler LIDAR sensors as remote sensors allow to obtain high spatial (5 m to 200 m) and temporal (1 Hz to 20 Hz) resolution and accurate wind measurement (typically 0.5 m/s). But the use of these sensors remains relatively limited for ATM and few are used for operational purposes in ATM. This paper presents the developments of a new generation of Doppler LIDAR systems for measuring wind and monitoring wind

hazards around airports. Their intrinsic performances in terms of measurement range and accuracy are described. Several applications of such LIDAR technology are then presented like wind measurements, wind shears detection and wake vortices monitoring thanks to several experiments performed on airports. As perspectives the paper proposes the potential benefits of using such atmospheric LIDAR sensors for optimizing air traffic like airport capacities and for improving air traffic safety.

Thobois, L. P. and Cariou, J. P.

"WIND MEASUREMENTS WITH GROUND-BASED FIBER-BASED WIND DOPPLER LIDAR SYSTEMS FOR AVIATION WEATHER APPLICATIONS"

AIAA Paper 2015-3399, June 2015, Dallas, TX.

In air traffic operations, weather is one of the major causes of flight delays and accidents. Among all the weather conditions for aircrafts, wind and wind hazards like wake vortices and wind shears require to be monitored with high spatial and temporal resolution sensors in order to reduce their impact on air traffic for improving safety and / or for optimizing ATM. Among the different available sensor technologies, Doppler LIDAR sensors as remote sensors allow to obtain high spatial (5 m to 200 m) and temporal (1 Hz to 20 Hz) resolution and accurate wind measurements (typical 0.5 m/s). But these sensors remain confidential and few are used for operational purposes. This paper will present the developments of a new generation of Doppler LIDAR systems for measuring wind and monitoring wind hazards around airports. Their intrinsic performances in terms of measurement range and accuracy will be described. Several applications of such LIDAR technology will be then presented like wind measurements, wind shears detection and wake vortices monitoring thanks to several experiments performed on airports. As perspectives the paper will propose the potential benefits of using such atmospheric LIDAR sensors for optimizing air traffic like airport capacities and for improving air traffic safety.

Thobois, L. P., Krishnamurthy, R., Cariou, J. P. and Nicolaon, J. P.

"DEPLOYMENT OF A NEXT GENERATION AND OPERATIONAL LIDAR SOLUTION FOR MONITORING WAKE VORTICES FOR SUPPORTING NEW WAKE TURBULENCE REGULATIONS"

AIAA Paper 2016-3273, June 2016, Washington, DC.

Numerous studies have been performed to better understand the behavior of wake vortices with regards to aircraft characteristics and weather conditions since ten years. These studies have led to the development of the aircraft recategorization (RECAT) programs. Its phase one focused on redefining distance separation matrix with six static aircraft wake turbulence categories. In Europe, the RECAT-EU regulation is now entering under operational implementation in several key airports. As proven by several research projects in the past, LIDAR sensors can be considered as the ground truth wake vortex measurements for assessing the safety impact of a new wake turbulence regulation at an airport in quantifying the risks given the local specificities. LIDAR's can also be used to perform risk monitoring after the implementation. In this paper, a methodology to measure wake vortices with scanning

coherent Doppler LIDARs is described as well as its contribution to the safety assessment and risk monitoring phases. The wake vortex algorithm used for post-processing the raw LIDAR data is presented and evaluated on limited datasets. Finally, the use of this LIDAR based solution for supporting the implementation of new wake turbulence regulation is described along with preliminary results of an on-going field campaign.

Thobois, L. P., Krishnamurty, R., Cariou, J. P., Dolfi-Bouteyre, A. and Valla, M.

"WIND AND EDR MEASUREMENTS WITH SCANNING DOPPLER LIDARS FOR PREPARING FUTURE WEATHER DEPENDENT SEPARATION CONCEPTS"

AIAA Paper 2015-3317, June 2015, Dallas, TX.

Since a decade, numerous studies have been performed to better understand the behavior of wake vortices in regards to aircraft characteristics and weather conditions. These studies have led to the development of the RECAT aircraft recategorization programs which consist for Phase one in redefining distance separation matrix for six static aircraft classes. If the benefits of such a new regulation have been demonstrated, highest benefits could be obtained with dynamic distance separations concepts with real time weather observations. In this context, new operational sensor technologies have been developed in the UFO European FP7 project to bring accurate and resolved observations that could be integrated into weather dependent separation ATM software. In this study, the methods developed for postprocessing radial data into wind vectors and turbulent eddy dissipation rate (EDR) will be presented as well as their validation with simulations or specific tests. The experiment performed at Toulouse-Blagnac airport in France will be described as well as the main sensors developed for the project. These methods will be then applied to the Toulouse LIDAR database. The results will be analyzed and compared with other sensors especially a research aircraft to assess the availability and accuracy of LIDAR data.

Thobois, L., Loaec, S., Cariou, J.-P. and Sauvage, L.

"MEASURING WAKE VORTICES AND WIND SHEARS IN REAL-TIME WITH A SCANNING WIND DOPPLER LIDAR"

92nd American Meteorological Society Annual Meeting, January 2012, New Orleans, LA.

Measuring and foreseeing wind conditions near airports are crucial issues for air traffic safety. Coherent laser radars or LIDARs can be very powerful devices for measuring wind shears on dangerous airports or wake vortices. LEOSPHERE has developed a scanning wind doppler lidar, the Windcube200S for these needs. Deployed on a French airport this lidar has been used to detect wake vortices and follow them under various atmospheric conditions. Given specific swept scenarios, the Windcube200S has been able to detect the wake vortices of heavy, medium, and small aircrafts during takeoff and landing. Wake vortices have been monitored for a period of 30 to 60 seconds that allowed to analyze their trajectories and their shapes evolution. Several analyses have been achieved in order to determine the influence of the wind conditions on the trajectories of wake vortices. Finally, a dedicated

post-treatment has been developed for identifying the cores of wake vortices and for calculating their circulations.

Thobois, L., Loaec, S., Cariou, J.-P. and Sauvage, L.

"MEASURING WAKE VORTICES AND WIND SHEARS IN REAL-TIME WITH A SCANNING WIND DOPPLER LIDAR"

WMO Technical Conference of Meteorological and Environmental Instruments and Methods, October 2012, Brussels, Belgium.

Measuring and foreseeing wind conditions near airports are crucial issues for air traffic safety. Since aircraft maneuverability is the worst during takeoff and landing phases, strong air movements near airports such as wind shears or wake vortices can have dramatic consequences on aircrafts. These phenomena are nevertheless very different since wind shears are generated by geography around airports, whereas wake vortices are created by aircrafts themselves. Wind shears usually appear in airports located near coasts, valleys, or mountains. These geographical items induce different winds in direction and in intensity depending on meteorological conditions. Wake vortices are generated by all the planes. Size and intensity of wake vortices are directly linked to the flight speed and by plane characteristics, such as weight and wingspan. Even if strong efforts have been done to study and model wind shears and wake vortices, on-site measurements remain the best way to detect them as they depend a lot on meteorological conditions near airports especially wind and turbulence. Coherent laser radars or LIDARs can be very powerful devices for measuring wind shears on dangerous airports or wake vortices. LEOSPHERE has developed a scanning wind doppler lidar, the Windcube200S for these needs. Deployed on a French airport in the framework of the European project SESAR, this lidar has been used to detect wake vortices and follow them under various atmospheric conditions. Given specific swept scenarios, the Windcube200S has been able to detect the wake vortices of heavy, medium, and small aircrafts during takeoff and landing. Wake vortices have been monitored for a period of 30 to 60 seconds that allowed to analyze their trajectories and their shapes evolution. Several analyses have been achieved to determine the influence of the wind conditions on the trajectories of wake vortices. A variety of trajectories have been put in front. Finally, a dedicated post-treatment has been developed for identifying the cores of wake vortices and for calculating their circulations.

Thom, A. and Duraisamy, K.

"HIGH-RESOLUTION SIMULATIONS OF PARALLEL BLADE-VORTEX INTERACTIONS"

AIAA Journal, Vol. 48, No. 10, October 2010, pp. 2313-2324.

The physics of a parallel blade-vortex interaction is studied numerically and the predicted pressure and acoustic results are compared with experimental measurements. A high-resolution solution of the compressible Euler equations is performed on structured overset meshes. Initially, a two-dimensional airfoil-vortex interaction is studied for both a case where the vortex misses the blade and a case of

direct impact. The vortex is initiated in the flow as a perturbation to the freestream conditions and is free to evolve, thus allowing for the deformation of the vortex as it interacts with the blade to be studied. The simulation is seen to accurately reproduce the experimental results and the emission of the acoustic waves from the airfoil surface is observed in detail. Acoustic energy generated by the interaction is seen to primarily radiate from the leading-edge section of the airfoil with a weaker contribution coming from the trailing edge. The simulations are then extended to three-dimensional moving overset meshes where the vortex generation and convection is also resolved. The numerical methodology is seen to accurately preserve the vortex strength and accurately reproduce the experimentally measured blade surface pressures and acoustics. The computations presented here face similar challenges to that encountered in the simulation of realistic helicopter blade-vortex interaction, but the computational costs are such that the solutions can be well resolved, and comprehensively validated using moderate resources.

Thom, A. D.

"ANALYSIS OF VORTEX-LIFTING SURFACE INTERACTIONS"

PhD Thesis, August 2011, University of Glasgow, Glasgow, Scotland.

The interaction of a vortex with a lifting surface occurs in many aerodynamic systems, and can induce significant airloads and radiate impulsive noise. Yet due to their complex nature, the ability to accurately model the important flow physics and noise radiation characteristics of these interactions in realistic situations has remained elusive. This work examines two cases of vortex-lifting surface interactions by enhancing the capabilities of a high-fidelity flow solver. This flow solver utilizes high spatial discretization accuracy with a fifth order accurate WENO scheme, and overset meshes to accurately resolve the formation, evolution and interaction of a tip vortex using an inviscid approximation of the fluid. An existing computational infrastructure is further developed and applied to analyze blade-vortex interactions that occur on a helicopter rotor. An idealized interaction is studied, where an independently generated vortex interacts with a rotor. It is found that through the employment of adequate spatial and temporal resolution, the current methodology can resolve the important details of the interaction over a range of vortex-blade miss distances. A careful study of the spatial and temporal resolution requirements is conducted to ensure that the computed results converge to the correct physical solution. It is also demonstrated that a linear acoustic analysis can accurately predict the acoustic energy propagated from these interactions to the far-field, provided the blade surface pressures are accurately computed. The methodology is then used to study an idealized propeller wake-wing interaction, which occur behind a tractor mounted turboprop. A computationally efficient method of modelling the wake-wing interaction is developed and the computed surface pressures of the interaction are confirmed to agree well with the experimental data. The analysis is coupled to an optimization algorithm to determine a novel wing design, and it is found that significant drag reductions can be achieved with small changes in the twist distribution of the wing.

Thomas, D. D.

"TURBULENCE RELATED ACCIDENTS, WORLDWIDE SYNOPSIS"

FAA Symposium on Turbulence, Federal Aviation Administration, Washington, DC, March 1971, p. 2.

Wake turbulence accidents are rare in air carrier operations, but clear air turbulence accidents are reaching the frequency of cloud associated accidents. One-half of all the turbulence accidents in general aviation are fatal, and one out of four of the total turbulence accidents involves wake vortex turbulence while clear air turbulence accidents are infrequent.

Thomas, M., Klipfel, S., Wilson, E. N. and Fahey, T.

"AN AIRLINE PERSPECTIVE: CURRENT AND FUTURE VISION FOR TURBULENCE FORECASTING AND REPORTING"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 11, 2016, Springer International Publishing Switzerland, pp. 227-242.

The flight planning process is the most critical time for the turbulence forecaster. It is the time that routes and altitudes are selected, and fuel is added for any necessary deviations. Aviation meteorologists can have a significant impact at this stage of flight planning. Internationally, flights are given preference for route and altitude selection based on the time the flight plan is filed. It is difficult for flights to change altitude once the flight plan has been accepted, since flights over the oceans cannot be seen on radar and have to be sequenced in space and time. If turbulence is not considered at the planning stage, altitude deviations for turbulence may not be allowed if there are other aircraft above and below the flight. Therefore, advanced knowledge of turbulence gives the advantage to the airlines that forecast turbulence accurately. The turbulence forecaster can also provide significant value during the flight following process. Monitoring real-time satellite and weather radar observations, as well as automated aircraft and manual pilot reports, can help verify model data and identify areas of un-forecasted turbulence. This enables Human-in-the-Loop adjustments to the Numerical Weather Prediction (NWP) models and ability to provide updates to flights while en route. A case study from 30 June 2014 over the upper Midwest USA demonstrates this process in detail. As NWP models improve, the role of the operational aviation meteorologist will evolve. In tandem, additional insight by the research community into the current operational forecast processes is important to successfully transition to automated turbulence forecasting. Improved methods of observing and reporting turbulence, and more efficient ways of distributing and displaying the turbulence forecasts for avoidance, will be needed.

Thomas, N. and Gunasekaran S.

"AFFECTING WINGTIP VORTEX BY INFLUENCING WING SURFACE-FLOW DIRECTION"

AIAA Paper 2018-0344, January 2018, Kissimmee, FL.

The aerodynamic efficiency of a NACA 0012 AR 4 wing was affected through periodic contours aligned in the flow direction resembling a wrinkled texture. Streamwise and cross-stream Particle Image

Velocimetry (PIV) were conducted at the University of Dayton Low Speed Wind Tunnel around Reynolds number of 135,000 on the NACA 0012 AR 4 wing with and without surface contours. Wings with 6 contour sections was designed by spline fitting two NACA 0012 airfoil profiles in the spanwise direction. Both 2D (wall-to-wall model) configuration and 3D configuration of the wings were tested to determine the effects of surface contours on the parasite and induced drag of the wing. Streamwise PIV results indicated an increase in momentum deficit in the wake of the mid-contour region due to enhanced boundary layer separation from the upper surface of the mid-contour region. The cross-stream PIV results indicated a decrease in the magnitude of azimuthal velocity, circulation, and RMS quantities in the wingtip vortex with the surface contours. The reduction in the wingtip vortex properties indicates that the contours were effective in blocking the spanwise flow feeding into the wingtip vortex on the surface of the wing.

Thomas, P. and Vogt, S.

"INTERCOMPARISON OF TURBULENCE DATA MEASURED BY SODAR AND SONIC ANEMOMETERS"

Boundary-Layer Meteorology, Vol. 62, 1993, pp. 353-359.

The capability of SODAR to measure the mean wind field in the lower boundary layer is well known and documented. Therefore, mean wind data are easily obtainable by means of the SODAR-technique, and are used to simulate the transport of pollutants after their release into the atmosphere. But when calculating the diffusion of pollutants, information about atmospheric turbulence is needed, too. In principle, a SODAR can measure turbulence data like the standard deviation of the vertical wind speed or horizontal wind direction. But when measuring turbulence data with a SODAR, one is beset by a host of limitations like volume sampling, spatial and temporal separation of sampling volume, attenuation of the acoustic waves and the slow speed of sound. Therefore, successful turbulence measurements with SODAR are not numerous and little is known about the quality of these data. In this context an intercomparison between a REMTECH-SODAR and a sonic anemometer mounted at the 100 m level of our meteorological tower was performed in summer 1990 at the Kemforschungszentrum Karlsruhe. The intercomparison is in two parts: (1) Half hour mean values of the standard deviation of the vertical wind speed are intercompared by scatter plots and by a linear regression and correlation analysis. (2) During 7 periods, 2 hours each, and covering atmospheric stabilities from unstable to slightly stable, the instantaneous vertical wind speeds were measured by both instruments and spectra were calculated. The intercomparison demonstrates that DOPPLER-SODAR sounding is a reliable technique to determine besides the mean field, also atmospheric turbulence data like $\Sigma(w)$.

Thomas, P. J. and Auerbach, D.

"THE OBSERVATION OF THE SIMULTANEOUS DEVELOPMENT OF A LONG- AND A SHORT-WAVE INSTABILITY MODE ON A VORTEX PAIR"

J. Fluid Mech., Vol. 265, 1994, pp. 289-302

Experiments on the stability of vortex pairs are described. The vortices (ratio of length to core diameter of up to 300) were generated at the edge of a flat plate rotating about a horizontal axis in water. The vortex pairs were found to be unstable, displaying two distinct modes of instability. For the first time, as far as it is known to the authors, a long-wave as well as a short-wave mode of instability were observed to develop simultaneously on such a vortex pair. Experiments involving single vortices show that these do not develop any instability whatsoever. The wavelengths of the developing instability modes on the investigated vortex pairs are compared to theoretical predictions. Observed long wavelengths are in good agreement with the classic symmetric long-wave bending mode identified by Crow (1970). The developing short waves, on the other hand, appear to be less accurately described by the theoretical results predicted, for example, by Widnall, Bliss & Tsai (1974).

Thomas, P. R., Bhandari, U., Bullock, S., Richardson, T. S. and du Bois, J. L.

"ADVANCES IN AIR TO AIR REFUELLING"

Progress in Aerospace Sciences, Vol. 71, 2014, pp. 14-35.

An increasing interest over the last decade in developing unmanned aerial systems' technologies has prompted research into methods for automating air to air refueling processes. Furthermore, for systems with increased autonomy the necessary logic and flight control systems to perform autonomous air to air refueling is now being pursued. There has already been significant research in position tracking, rendezvous scheduling, apparatus modelling, wake effects, and vision-based sensors to support refueling of unmanned systems and to increase the autonomy in manned aircraft refueling. Many of these build upon considerable research and understanding that has matured for manned air to air refueling. This paper reviews the current, and future, state of research in this area.

Thomer, O., Klaas, M. and Schroder, W.

"OBLIQUE SHOCK-VORTEX INTERACTION"

Proc. Appl. Math. Mech., Vol. 2, 2003, pp. 334-335

Breakdown of a slender vortex caused by an oblique shock is studied using numerical solutions of the Euler equations for unsteady three-dimensional flow. A Burgers vortex with a given circulation and axial velocity distribution is prescribed at the inflow boundary. The calculations show that like in incompressible flows supersonic breakdown is primarily controlled by pressure forces. The shock is deformed into an 's'-shaped part near the vortex core where the shock becomes normal. The results indicate that initiation of breakdown is more sensitive to variations in the axial velocity than in the circulation, and that the flow structure is clearly time-dependent.

Thomer, O., Krause, E. and Schroder, W.

"INTERACTION BETWEEN LONGITUDINAL VORTICES AND NORMAL AND OBLIQUE SHOCKS"

In *Vortex Dominated Flows*, edited by D. Blackmore, E. Krause and C. Tung, 2005, World Scientific, New Jersey, Chapter 12, pp. 199-227.

Breakdown of a slender vortex caused by normal (NSVI) and oblique shocks (OSVI) is studied using numerical solutions of the Euler and Navier-Stokes equations for unsteady, three-dimensional, supersonic flow at free stream Mach numbers of 1.6 and 2.0. At the inflow boundary a slender Burgers vortex with a given circulation and axial velocity distribution is prescribed. The calculations using approximately 2 million grid points show that breakdown is primarily controlled by pressure forces and is therefore easily initiated when the vortex interacts with a normal shock. Oblique shocks are deformed into an 's'-shaped part near the vortex core where the shock becomes normal. The results also indicate that initiation of breakdown is more sensitive to variations in the axial velocity component than in the circulation of the vortex, and that the flow structure is time-dependent. A simple breakdown criterion based on the axial momentum flux is presented for both NSVI and OSVI.

Thomer, O., Schroder, W. and Krause, E.

"NUMERICAL INVESTIGATIONS ON SUPERSONIC VORTEX BREAKDOWN"

Proceedings in Applied Mathematics and Mechanics, Vol. 1, 2002, pp.310-311.

Breakdown of a slender vortex caused by a normal shock is studied using a numerical solution of the Navier-Stokes equations for unsteady, three-dimensional, supersonic flow at a free stream Mach number of 1.6. The numerical results clearly reveal the time-dependent flow structure for both the axial and the radial direction. The results compare well with recent experimental findings.

Thomer, O., Schroder, W. and Krause, E.

"NORMAL SHOCK VORTEX INTERACTION"

RTO AVT Symposium on 'Advanced Flow Management: Part A - Vortex Flows and High Angle of Attack for Military Vehicles', Loen, Norway, May 2001.

Breakdown of a slender longitudinal vortex caused by a normal shock is studied with a numerical solution of the EULER and the NAVIER-STOKES equations for time-dependent, three-dimensional, supersonic flow at a free stream MACH number of 1.6 and different vortex strengths. When breakdown occurs, a free stagnation point is formed downstream from the shock, followed by a region of reversed flow with a bubble-like flow structure. The burst part of the vortex grows in the axial and radial directions until the bubble reaches a stable position. The shock remains normal near the axis of the vortex but is curved further away from it. The flow downstream from the shock is slightly oscillating. The numerical results clearly reveal the time-dependent flow structure in the axial and the radial direction. The results compare well with recent experimental findings.

Thomer, O., Schroder, W. and Krause, E.

"NORMAL AND OBLIQUE SHOCK-VORTEX INTERACTION"

Proceedings of International Conf. RDAMM-2001, June 2001, Novosibirsk, Russia, pp. 737-749.

Breakdown of a slender vortex caused by normal and oblique shocks is studied using numerical solutions of the Euler and Navier-Stokes equations for unsteady, three-dimensional, supersonic flow at free stream Mach numbers of 1.6 and 2.0. At the inflow boundary a Burgers vortex with a given circulation and axial velocity distribution is prescribed. The calculations using approximately 2 million grid points show that breakdown is primarily controlled by pressure forces and is therefore easily initiated when the vortex interacts with a normal shock. Oblique shocks are deformed into an 'S'-shaped part near the core where the shock becomes normal. The results also indicate that initiation of breakdown is more sensitive to variations in the axial velocity than in the circulation, and that the flow structure is clearly time-dependent.

Thompson, D. H.

"A PRELIMINARY TOWING TANK STUDY OF THE TRAILING VORTEX GENERATED BY A RECTANGULAR WING, INCLUDING THE EFFECTS OF SEVERAL TIP MODIFICATIONS"

ARL/A-Note-342, September 1973, Aeronautical Research Labs., Melbourne, Australia

The structure of the trailing vortex generated by a rectangular wing in a small towing tank has been studied using the hydrogen bubble flow visualization technique. The effects on the vortex of starting and stopping the towing carriage and of passing a body through the vortex core have been examined. A total of fourteen modifications to the basic wing have been tested for the effect of each on the trailing vortex.

Thompson, D. H.

"EXPERIMENTAL STUDY OF AXIAL FLOW IN WING TIP VORTICES"

J. Aircraft, Vol. 12, No. 11, November 1975, pp. 910-911

This note describes a qualitative towing tank study of some of the factors which control the axial flowfield in a trailing vortex and attempts an explanation of the differing results of previous axial velocity measurements. The towing tank tests showed that the axial velocity distribution in a wing tip vortex can take the form of a centerline velocity excess, a centerline velocity deficit, or a centerline velocity combined with a core edge velocity excess. The velocity distribution at any station behind the wing depends on the wing section, tip shape, Reynolds number, wing incidence and distance of the station from the wing.

Thompson, J. F., Shanks, S. P. and Wu, J. C.

"NUMERIC SOLUTION OF THREE-DIMENSIONAL NAVIER-STOKES EQUATIONS SHOWING TRAILING TIP VORTICES"

AIAA Journal, Vol. 12, No. 6, June 1974, pp. 787-794

Numerical solution of the incompressible Navier-Stokes equations in integro-differential form is applied to time-dependent flow about a rectangular slab at an angle of attack. With this formulation the solution is obtained in the entire unbounded flowfield, but with actual computation required only in regions of significant vorticity. This allows considerable reduction in computer storage, since only points in regions of significant vorticity need be stored at any time. The computational field thus expands in time. (This method is not to be confused with 'vortex methods' using discrete vortices and images.) The finite numerical calculation field in the integro-differential formulation is, in effect, infinite, and the necessity of locating 'infinity' at a finite distance is avoided. Although it is not necessary in this numerical method to calculate the velocity at points outside the region of nonzero vorticity, the velocity at these points and, in fact, to infinity, is determined by the solution via an integral over the vorticity distribution. The method requires two orders of magnitude less computer storage than do methods based on the differential formulation. Results have been obtained for the development of trailing tip vortices and the force coefficients.

Thompson, S. D.

"TERMINAL AREA SEPARATION STANDARDS: HISTORICAL DEVELOPMENT, CURRENT STANDARDS, AND PROCESSES FOR CHANGE"

ATC-258, Jan. 1997, MIT Lincoln Laboratory, Lexington, MA.

This paper gives an overview and summary of the separation requirements for air traffic control in the U.S. National Airspace System with emphasis on those relevant to terminal landing operations. These requirements are documented in the FAA's Air Traffic Control Order 7110.65J, as amended, and various national and local Orders. These requirements are also addressed in the Aeronautical Information Manual, the International Civil Aviation Organization's Standards and Recommended Practices, and the Federal Aviation Regulations. The purpose of this paper is to assist those people involved with the introduction of new technologies and procedures in the terminal airspace by providing them with an understanding of the separation requirements, the need for those requirements, and the processes used to change the requirements.

Thompson, T. L., Komerath, N. M. and Gray, R. B.

"VISUALIZATION AND MEASUREMENT OF THE TIP VORTEX CORE OF A ROTOR BLADE IN HOVER"

Journal of Aircraft, Vol. 25, No. 12, Dec. 1998, pp. 1113-1121

Detailed measurements with a laser Doppler velocimeter (LDV) have been performed in the tip region and in the tip vortex core of a single-bladed model rotor in hover. The testing was conducted at a rotor tip speed of 32 m/s, a Reynolds number of 269,000, and at two values of the rotor thrust coefficient, 0.0022 and 0.0057. Strobed laser sheet flow visualization was used to verify the steadiness of the tip vortex trajectory in the near wake and quantify the vortex trajectory to guide LDV surveys of the vortex core. A remotely aligned off-axis receiving optics system enabled measurement of vortex core velocity

profiles at large focal lengths. The core self-induced velocity components extracted from these data are presented. The data exhibit evidence of secondary structure even inside the rotational core of the vortex. The axial velocity profile along the core has been extracted and presented in the wake of a spinning rotor. It is seen that the tip vortex of a rotating blade differs considerably in structure from a fixed-wing vortex.

Thomson, J. A. L. and Hannon, S. M.

"WAKE VORTEX MODELING FOR AIRBORNE AND GROUND-BASED MEASUREMENTS USING A COHERENT LIDAR"

Proceedings of the Conference, Air Traffic Control Technologies, Orlando, FL, April 18-19, 1995, Society of Photo-Optical Instrumentation Engineers (SPIE) Proceedings, Vol. 2464, 1995, pp. 63-78

Simulated signatures of aircraft wakes as detected by a scanning coherent short wavelength lidar are presented and characterized for several candidate surveillance scenarios. Ground-based and airborne scanning configurations that emulate candidate operational detection and warning systems are compared for spatial coverage and detection capability as a function of system design parameters and atmospheric conditions. Examples of trailing geometries characteristic of onboard wake detection and warning systems are presented. The dependence of predicted detection capability on hydrodynamic parameters, such as vortex circulation, axial motion in the wake vortices, and ambient turbulence is discussed. Simulated wake signatures are compared to observations for wakes observed at Denver's Stapleton International Airport in 1993.

Thomson, J. A. L. and Huffaker, R. M.

"2 MICRON COHERENT LASER RADAR FOR ON-BOARD AIRCRAFT VORTEX WAKE DETECTION: PATTERN RECOGNITION TECHNIQUES AND TECHNOLOGY ASSESSMENT"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 42-1 - 42-27

A model for estimating the performance of a coherent lidar for detecting and tracking aircraft vortex wakes is described. The goal of the analysis is to assess and predict detection performance of the coherent lidar system as a function of its design and in a variety of operating environments. For this purpose, an existing laser system performance simulator has been modified to apply to aircraft wake detection. The model has three basic elements: a description of the velocity and scattering properties of the wake itself, a specification of the laser optics and scanning procedures, and a simulation and error analysis of the data processing algorithms. Standard models for atmospheric absorption, scattering and coherence loss together with representations of ambient turbulence are used to describe the operating environment. The numerical simulation provides a detailed emulation of the characteristics of the laser signal returned from the atmosphere. Pulsed, CW, focused and unfocused configurations can be simulated. Various measures of performance can be implemented ranging from simple Doppler exceedances along given lines of sight to relatively complex 2D and 3D pattern

recognition concepts. In this paper, spatial displays will be used of the detected pattern of line-of-sight velocity and Doppler spread as well as spatial displays of the probability that a given vortex wake is present as a function of its hypothesized position (matched filter detection).

Thomson, J. A. L. and Meng, J. C. S.

"SCANNING LASER DOPPLER VELOCIMETER SYSTEM SIMULATION FOR SENSING AIRCRAFT WAKE VORTICES"

J. Aircraft, Vol. 13, No. 8, August 1976, pp. 605-613

The objectives of this study are to simulate the responses of the Scanning Laser Doppler Velocimeter System in a vortex wake environment and to display the spatial signatures. From analysis of these signatures and future parallel processing of flight data and simulated data, optimal detection tactics can be established. A hydrodynamic model is developed that represents the trailing vortex sheet and wind shear as discrete free vortices distributed over a two-dimensional grid. The effects of buoyant exhaust and atmospheric stratifications can be incorporated in the Boussinesq approximation; the atmospheric turbulence can be simulated by constructing specific realization.

Thomson, J. A. L. and Meng, J. C. S.

"SIMULATION AND DATA ANALYSIS OF A SCANNING LASER DOPPLER VELOCIMETER"

Proceedings Minnesota Symposium on Laser Anemometry, Univ. Minnesota, Minneapolis, 1976, pp. 231-276

The paper discusses the spectral signal characteristics of coaxial scanning laser Doppler velocimeter systems which are relevant to the modeling of the response of such systems to simulated and actual aircraft vortex wakes transported through the atmosphere. Some examples of the analysis of the measurements on real and simulated wakes are presented.

Thomson, J. A. L. and Meng, J. C. S.

"LASER DOPPLER VELOCIMETER SYSTEM SIMULATION FOR SENSING AIRCRAFT WAKE VORTICES, PART I: SIMULATION MODEL"

PD-74-058, December 1974, Physical Dynamics Inc., Berkeley, C.

A hydrodynamic model of aircraft vortex wakes moving in a turbulent wind shear field near the ground is developed and used as a basis for modeling the characteristics of a laser Doppler detection and vortex location system. The trailing vortex sheet and the wind shear are represented by discrete free vortices distributed over a two-dimensional grid. The time dependent hydrodynamic equations are solved by direct numerical integration. The effects of buoyant exhaust and atmospheric stratifications are incorporated in the Boussinesq approximation. The ground boundary is simulated by images, and fast Fourier Transform techniques are used to evaluate the vorticity stream function. The

response of a simulated laser Doppler velocimeter is analyzed by simulating the signal return from the flow field as sensed by a simulation of the optical/electronic system.

Thong, C. W. S.

"MODELING AIRCRAFT PERFORMANCE AND STABILITY ON X-PLANE"

Thesis, 2010, The School of Engineering and Information Technology (SEIT), UNSW Canberra, Campbell, Australia.

Commercial flight simulator software has been long used by the public to hone their piloting skills. X-Plane is the first commercially available flight simulator program which directly outputs mathematical flight data without the need for programming knowledge. This allows the public to readily simulate flight tests on a computer and acquire flight test data. This thesis models the F-15E in X-Plane and compares its performance and handling characteristics to those predicted by theory and flight manual data. These comparisons will be used to determine X-Plane's usefulness as a teaching and analytical tool in the demonstration of how forces and moments affect an aircraft's flight path in flight.

Thorpe, R. L., McCrink, M. H. and Gregory, J. W.

"MEASUREMENT OF UNSTEADY GUSTS IN AN URBAN WIND FIELD USING A UAV-BASED ANEMOMETER"

AIAA Paper 2018-4218, June 2018, Atlanta, GA.

This paper presents the development and testing of an unmanned aerial vehicle (UAV) for measurement of turbulent wind gusts in an urban wind field. This UAV is equipped with a 3-axis sonic anemometer capable of sampling at rates up to 200 Hz. The key advantage of these vehicles is the ability to position the UAV at any desired point in a wind field without the restrictions of fixed towers. The challenge of this configuration is the spatial and temporal integration of a flight controller's attitude data with separate wind speed readings. Furthermore, the measured wind data from the anemometer must be corrected for induced velocities from the vehicle's motion. The focus of this paper is on the development of accurate correction schemes to remove the induced velocity components caused by the rotation and translation of the flight vehicle.

Thurrow, B. S., Fahringer, T., Johnson, K. and Hellman, S.

"COMPARISON OF PLENOPTIC PIV AND STEREO PIV MEASUREMENTS IN A WING TIP VORTEX"

17th International Symposium on Application of Laser Techniques to Fluid Mechanics, July 2014, Lisbon, Portugal.

The visibility of a first generation plenoptic PIV system is assessed through comparison with stereo PIV measurements of a wing tip vortex produced by a flat plate at an 8-degree angle of attack. Stereo PIV measurements were acquired in a streamwise plane through the approximate center of the vortex and highlight the presence of the vortex through measurement of the out-of-plane component of

velocity. Instantaneous velocity images indicate that the vortex was interacting with the street like wake produced by the sharp-edged plate. Plenoptic PIV produced instantaneous and average 3D/3C velocity images that clearly show the three-dimensional position of the wing tip vortex along with other features of the flow. The average flow field also displays clear evidence of the interaction between the forming wing tip vortex and the wake. Trends in streamwise averaged velocity profiles were similar between the two systems, although the magnitudes varied with differences attributed to the decreased spatial resolution of the plenoptic camera, the limited number of plenoptic PIV samples and the need for a more robust alignment between the two camera systems. Overall, plenoptic PIV is shown as a viable and convenient method for acquisition of volumetric velocity data. Its primary strength is that it is a single camera technique, which results in a relatively simple experimental arrangement comparable to conventional 2D PIV. Presently, its chief drawback is low spatial resolution and limited dynamic range, although next generation cameras promise significant improvements in both.

Tian, P., Chao, H., Gu, Y. and Hagerott, S. G.

"UAV FLIGHT TEST EVALUATION OF FUSION ALGORITHMS FOR ESTIMATION OF ANGLE OF ATTACK AND SIDESLIP ANGLE"

AIAA Paper 2016-0645, January 2016, San Diego, CA.

Angle of attack (AOA) and angle of sideslip (AOS) are critical states for aerodynamic modeling of flight vehicles. They can provide pilots with important safety information for stall avoidance, or serve as feedback for control purposes. More importantly, AOA and AOS are good indications of aircraft encounters with dynamic flow fields, such as thermal, gust, and wake vortices. Such measurements can be used for the detection and identification of the flow model parameters when combined with other onboard sensors. However, it is difficult to get accurate AOA and AOS measurements especially with low-cost small unmanned aerial vehicles (UAVs). This paper provides a thorough evaluation of three commonly used fusion algorithms for AOA and AOS estimation, using UAV flight data in ambient turbulence as well as wake turbulence. The performance of these algorithms is compared both in simulation and through flight test data.

Tian, P., He, A., Chao, H., Zheng, Z. C. and Gu, Y.

"WAKE ENCOUNTER SIMULATION AND FLIGHT VALIDATION WITH UAV CLOSE FORMATION FLIGHT"

AIAA Paper 2017-1910, January 2017, Grapevine, TX.

In this paper, HawkWakeSim, a novel UAV wake encounter simulation platform, is presented with coupled modeling of aerodynamics and flight dynamics. Unlike conventional aircraft simulation models where aerodynamic coefficients are identified from flight test data, HawkWakeSim uses results from computational fluid dynamics calculations and updates the aerodynamic coefficients at each time step, which eliminates the errors from linearization. Several wake encounter scenarios with different lateral encounter angles and following clearances are simulated and investigated. The aircraft responses in one of the simulated scenarios are compared with experimental data obtained from a UAV close formation flight. Results from HawkWakeSim match the overall trend of flight test results, which show

its effectiveness. Additionally, aircraft responses during wake encounters under different control configurations are simulated and analyzed.

Tian, W., Ozbay, A., Sarakar, P. and Hu, H.

"AN EXPERIMENTAL STUDY ON THE PERFORMANCE OF WIND TURBINES OVER COMPLEX TERRAIN"

AIAA Paper 2013-0612, January 2013, Grapevine, TX.

An experimental study was conducted to investigate the performance of wind turbines over hilly terrains to elucidate the underlying physics to explore/optimize design of wind turbines sitting over complex terrains for higher power yield and better durability. The experiments were conducted in an atmospheric boundary layer wind tunnel with turbines sited over a two-dimensional hill. In addition to measuring dynamic wind loads and the power outputs of the wind turbines, detailed flow field measurements were also made to quantify the flow characteristics of the surface wind and the wake interference among multiple wind turbines over hilly terrain. The detailed flow field measurements were correlated with the wind load and power output measurements of the wind turbine models to explicate the physical mechanisms associated with power generation and fatigue loads acting on the wind turbines for the optimal design of the wind turbine layout over complex terrain.

Tian, Y., Sun, J., Wan, L.-l. and Li, Y.-q.

"SEPARATION DETERMINING METHOD OF CLOSELY SPACED PARALLEL RUNWAYS"

Journal of Traffic and Transportation Engineering, Vol. 13, No. 1, February 2013, pp. 70-76.

By using wake vortex movement characteristics under the most adverse environment, the effects of the slant range and approach glide angles of paired aircrafts and aircraft type combination on runway separation under the dependent parallel approach mode of closely spaced parallel runways were researched, the minimum wake vortex separation standard and crosswind statistical data of NASA were used, and the determination methods of runway centerline distance and threshold offset were put out based on aircraft type parameters. Analysis result shows that when the slant separation standard of paired leading and trailing aircrafts is a certain value, threshold offset decreases with the increases of runway centerline distance and the glide angle of paired trailing aircraft. When the glide angles of paired leading and trailing aircrafts are same, threshold offset decreases with the increases of runway centerline distance and slant separation standard. When runway centerline distance is 380 m, the glide angles of paired leading and trailing aircrafts are both 3 degrees, and slant separation standard is 2 780 m, the threshold offset of Changsha Huanghua International Airport should be more than 1 483 m, which is accord with the runway parameter of foreign authorized airports. [In Chinese].

Tieleman, H. W. and Tavoularis, S. C.

"AN INSTRUMENTATION SYSTEM FOR THE MEASUREMENT OF ATMOSPHERIC TURBULENCE"

Journal of Industrial Aerodynamics, Vol. 2, 1977, pp. 49-63.

A method is described for the detailed multi-point measurement of the turbulent velocity components and temperature in the atmospheric surface layer. The TSI three-dimensional split-film anemometer system is used as sensor and a special designed data acquisition and data-handling system is used for the sampling, digitizing and storing of the data on digital magnetic tapes. Further processing of the data is performed in a digital computer and programs are developed to allow efficient calculation of the statistical quantities such as, mean values, covariance, power- and cross-spectral density functions. At the present, six anemometer systems have been mounted on the 30-, 50-, 100-, 150-, 200- and 250-foot levels of the 250-foot Meteorological Tower at NASA, Wallops Flight Center. The tower is located at Wallops Island which is one of the barrier islands protecting the so-called 'Delmarva' peninsula from the Atlantic Ocean. The island, which consists of a narrow strip of dunes approximately three meters above sea level, is situated in a northeast-southwest direction and is separated from the mainland by a three-mile-wide tidal swamp.

Tilman, P.

"PROPAGATION OF SOUND RADIATION THROUGH VORTICES: A CONTRIBUTION TO THE THEORY OF FLOW MEASUREMENT WITH ULTRASOUND"

Report 6/1972, 1972, Max Planck Institut für Stromungsforschung, Göttingen, Germany

The circulation and core diameter of vortices are determined from the frequency distribution of the phase deviations (phase spectra) of an ultrasonic wave propagation through a wake. Theoretical principles are developed which make use of the geometrical acoustic approximation. An exact solution of the canonical equations for the development of acoustic radiation in the potential vortex is presented in integral form, and a closed solution for the corresponding problem in the rigidly rotating vortex core is indicated. A simplified application of these solutions leads to a method for the approximate determination of the vortex core diameter from the phase spectra.

Timm, G. K.

"SURVEY OF EXPERIMENTAL VELOCITY DISTRIBUTIONS IN VORTEX FLOWS WITH BIBLIOGRAPHY"

Report D-82-0683, November 1967, Boeing Scientific Research Labs, Seattle, WA

Vortex flow is basic to and of great importance throughout fluid dynamics. Experimental data on circumferential velocities in real vortices was determined mostly for vortex flows generated by straight wings and delta wings. A literature search was conducted to collect pertinent data and to present a unified picture of present experimental knowledge. Circumferential velocity distributions in using vortices determined in four investigations are set forth in which there was an acceptable degree of confidence in the instrumentation techniques and data analysis. A bibliography on vortex flows is also prescribed.

Ting, J. and Lan, C. E.

"NAVIER-STOKES CALCULATION OF AERODYNAMIC CHARACTERISTICS OF WINGS IN VORTEX WAKE ENCOUNTER"

AIAA Paper No. 1997-2267, Atlanta, GA, June 1997

The main purpose of the paper is to use a Navier-Stokes solver to compute the induced aerodynamics on a wing intercepting the vortex wake of a generating wing. Viscosity plays an important role in developing a thick, deflected wake in the in-tunnel simulation. The present investigation is restricted to an axial penetration of the wake by the encountering wing. In addition to the induced rolling moment, the change in longitudinal aerodynamics with respect to the vertical position of the following wing relative to the upstream vortex-generating wing will also be investigated.

Ting, L.

"PERTURBATION PROBLEMS IN FLUID MECHANICS"

Report 92-11-06, November 1992, Courant Institute of Mathematical Sciences, New York NY.

Perturbation methods and numerical methods were employed to study five problem areas. (1) For viscous vortical flows, a complete account of the asymptotic analyses, numerical studies and their physical meaning was presented in Springer-Verlag Lecture Notes in 1991. An extension of the asymptotic analysis for the motion and diffusion of a slender vortex filament to allow for the variation of the core structure along the filament was accomplished in 1992. This extension was needed for the study of the vortex breakdown problem. (2) For shock wave interactions, the locations and the types of singularities in the interaction of semilinear waves in three- and higher dimensional space were identified. (3) For wave propagations in a bubbly liquid, a survey of the linear and nonlinear theories and their limitations was presented in an article in *Advances in Applied Mechanics* in 1991. A system of effective equations uniformly valid at small gas volume fraction and large bubble number density was derived in 1992. (4) For free boundary problems, solutions simulating the breaking up or merging of symmetric slender jets or thin sheets were obtained in 1990. The solution for drop formation after the breaking was formulated recently. (5) In the analysis of structural/acoustic interactions, the solution for the panel oscillation was uncoupled from that for the acoustic field by the recent formulation of the on-surface conditions considering the acoustic effect.

Ting, L.

"STUDIES IN THE MOTION AND DECAY OF VORTICES"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 11-39

Solutions of Navier-Stokes equations are constructed as an asymptotic expansion in terms of a small parameter related to the Reynolds number of the vortex. A general scheme is presented for the matching of the inner viscous core of the vortex to the outer inviscid solution. The singularities in the inviscid theory are removed and the condition of regularity in the flow field defines the velocity of the

vortex line. This general scheme is applied to study vortices in two dimensional, axially symmetric and in three-dimensional flow fields. Results for the outer solution which do or do not require the solution in the viscous core are obtained separately.

Ting, L.

"STUDIES ON THE MOTION AND DECAY OF A VORTEX FILAMENT"

Lecture Notes in Physics, Vol. 148, 1981, pp. 67-105.

A review of asymptotic analyses for the study of the motion and decay of a vortex filament submerged in a background potential flow is presented. Emphasis is placed on physical intuitions motivating the analyses and on the physical interpretation of the asymptotic solutions. The extension of the analyses to a vortex filament submerged in a rotational flow is outlined. The asymptotic analyses identify various canonical problems which require numerical solutions of the Navier-Stokes equations. These numerical studies in turn initiate new theoretical analyses.

Ting, L.

"STUDIES ON THE MOTION AND DECAY OF A VORTEX FILAMENT"

Advances in Fluid Mechanics, Lecture Notes in Physics, Vol. 148, 1981, pp. 67-105.

A review of asymptotic analyses for the study of the motion and decay of a vortex filament submerged in a background potential flow is presented. Emphasis is placed on physical intuitions motivating the analyses and on the physical interpretation of the asymptotic solutions. The extension of the analyses to a vortex filament submerged in a rotational flow is outlined. The asymptotic analyses identify various canonical problems which require numerical solutions of the Navier-Stokes equations. These numerical studies in turn initiate new theoretical analyses.

Ting, L. and Tung, C.

"ON THE MOTION AND DECAY OF A VORTEX IN A NON-UNIFORM STREAM"

PIBAL-851, August 1964, Polytechnic Institute of Brooklyn, Brooklyn, NY

A systematic procedure is presented for the study of the motion of a vortex in a two-dimensional, incompressible, nonuniform stream as a solution of the Navier-Stokes equations by the introduction of a small parameter ϵ , which is inversely proportional to the square root of the Reynolds number of the vortex. Two different sets of length and time scales are introduced. The set with longer length and time scales is identified with the typical scales of the outer nonuniform flow. The ratio of the two length scales and that of the time scales are powers of the small parameter ϵ . By the expansion of the solutions in the power of ϵ with appropriate time and length scales, it is shown that the outer solution of the Navier-Stokes equations will be the same as the inviscid solution, and the leading term in the

inner solution agrees with that of a decaying axially symmetric vortex. The singularity associated with an inviscid vortex is removed.

Ting, L. and Tung, C.

"MOTION AND DECAY OF A VORTEX IN A NONUNIFORM STREAM"

Phys. Fluids, Vol. 8, No. 6, June 1965, pp. 1039-1051

The motion of a vortex in a two-dimensional incompressible nonuniform stream is studied by including the viscous effects in the inner core of the vortex. A systematic procedure is presented by the introduction of two different sets of length and time scales with the larger scales identified with the typical scales of the outer nonuniform flow. The ratios of the scales are powers of the small parameter ϵ which is inversely proportional to the square root of the Reynolds number of the vortex. It is shown that the leading term of the solution to the Navier-Stokes equations is composed of the classical inviscid solution matched with the solution of a decaying axially symmetric vortex. Thus, the singularity in the center of the vortex associated with the classical inviscid theory is removed. The next-order solution shows that the time average of the velocity of the center of the vortex over a period of the order of the larger time scale should agree at least to the order of ϵ^2 with the local space mean of the velocity of the outer inviscid flow which has been assumed to be the velocity of the center of the vortex in the classical inviscid theory of vortex motion.

Ting, L., Klein, R. and Knio, O. M.

"ASYMPTOTIC THEORY OF SLENDER VORTEX FILAMENTS -- OLD AND NEW"

Proceedings IUTAM Symposium on Dynamics of Slender Vortices, September 1997, Aachen, Germany.

We give a brief historical account of the asymptotic theories of the motion of slender vortices and the evolution of the core structures. We emphasize the motivations, the choice of length and time scales for a given problem and explain the physical meaning of the asymptotic solutions and the consistency conditions for the core structures. We present some highlights of the extensions of the asymptotic theories in the past decade. They include the use of multiple length scales in the axial variation of the core structure and in the interaction of filaments. The study of the interaction of filaments with a solid body and sound generation, and the applications of asymptotic theory to numerical simulations and experimental investigation of slender vortex dynamics are also presented. We then describe a few vortical flow problems currently under investigation.

Tingey, E. B. and Ning, A.

"PARAMETERIZED VERTICAL-AXIS WIND TURBINE WAKE MODEL USING CFD VORTICITY DATA"

AIAA Paper 2016-1730, January 2016, San Diego, CA.

In order to analyze or optimize a wind farm layout, reduced-order wake models are often used to estimate the interactions between turbines. While many such models exist for horizontal-axis wind turbines, for vertical-axis wind turbines (VAWTs) a simple parametric wake model does not exist. Using computational fluid dynamic (CFD) simulations, we computed vorticity in a VAWT wake, and parameterized the data based on normalized downstream positions, tip-speed ratio, and solidity to predict a normalized wake velocity deficit. When compared to CFD, which takes about a day to run one simulation, the reduced-order model predicts the velocity deficit at any location within 5-6 percent accuracy in a matter of milliseconds. The model was also found to agree well with trends observed in experimental data. Future additions will allow the reduced-order model to be used in wind farm layout analysis and optimization by accounting for multiple wake interactions.

Tinling, B. E.

"ESTIMATION OF VORTEX-INDUCED ROLL EXCURSIONS BASED ON FLIGHT AND SIMULATION RESULTS"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FA-RD-77-68, June 1977, pp. 11-22

The results of flight measurements at altitude were combined with an analytical procedure to estimate the wake vortex roll excursions for aircraft ranging in size from small business jets to jumbo jets. The roll excursion estimates were compared with a bank-angle boundary developed from piloted simulation. The estimates indicate that if the vortex from a jet transport of medium size or larger should be encountered out of ground effect at current separation distance standards, the resulting maximum bank angle exceeds the boundary for all following aircraft except the large heavy transports. The possible bank-angle excursion for small aircraft, even though their separation distances are greater, exceeds the boundary by a large amount. In view of this apparent hazard, it is reasoned that the current extremely low accident rate exists because the specified separation allows sufficient time for the vortices to be removed from the path of following aircraft by winds and by their mutual induction, and because the vortex strength is dissipated at low altitudes by ground effect.

Tinling, B. E.

"ESTIMATES OF THE EFFECTIVENESS OF AUTOMATIC CONTROL IN ALLEVIATING WAKE VORTEX INDUCED ROLL EXCURSIONS"

NASA TM X-73267, August 1977, NASA Ames Research Center, Moffett Field, CA

Estimates of the effectiveness of a model following type control system in reducing the roll excursion due to a wake vortex encounter were obtained from single degree of freedom computations with inputs derived from the results of wind tunnel, flight, and simulation experiments. The analysis indicates that the control power commanded by the automatic system must be roughly equal to the vortex induced roll acceleration if effective limiting of the maximum bank angle is to be achieved.

Titchener, I. M. and Taylor-Russell, A. J.

"EXPERIMENTS ON THE GROWTH OF VORTICES IN TURBULENT FLOW"

ARC Technical Report C.P. No. 316, 1957, Imperial College, London, England.

Measurements of the flow in turbulent line vortices along the center of a pipe have been made to determine the growth of trailing vortices in the wake of an airplane. It is found that the rate of growth is small and of the same order as for a laminar line vortex.

Titcher, I. M. and Taylor-Russell, A. J.

"EXPERIMENTS ON THE GROWTH OF VORTICES IN TURBULENT FLOW"

ARC Report CP-316, March 1956, Imperial College, London, England

Measurements of the flow in turbulent line vortices along the center of a pipe have been made to determine the growth of trailing vortices in the wake of an airplane. It is found that the rate of growth is small and of the same order as for a laminar line vortex.

Titon, J. H. and Cadot, O.

"LARGE SCALE POWER FLUCTUATIONS AND DYNAMIC PROPERTIES OF ISOLATED VORTICES IN A TURBULENT FLOW"

Lecture Notes in Physics, Vol. 555, 2000, pp. 309-315

We present preliminary results concerning the correlation between fluctuations of power injected at large scales in a turbulent flow and the dynamic properties of low pressure filaments. Those two physical variables have already been studied, one at a time, in similar experimental geometries.

Tittsworth, J. A., Lang, S. R., Johnson, E. J. and Barnes, S.

"FEDERAL AVIATION ADMINISTRATION WAKE TURBULENCE PROGRAM -- RECENT HIGHLIGHTS"

57th Air Traffic Control Association Annual Conference and Exposition, October 2012, Gaylord, MD.

The current paper highlights the recent progress and ongoing development of the Federal Aviation Administration's wake turbulence program activities. The relevance of the topic to NextGen and a brief historical account on the problem is given first. The paper then describes in some detail four specific wake turbulence solutions that are either being developed or implemented, which are (1) FAA Order 7110.308 authorizing simultaneous dependent approaches with 1.5nm diagonal separation to Closely Spaced Parallel Runways, (2) Wake Turbulence Mitigation for Departures (WTMD), (3) Wake Turbulence

Mitigation for Arrivals (WTMA) and (4) Wake Turbulence Recategorization. All of these solutions directly support NextGen's objective for capacity enhancement goals.

Tobin, N., Hamed, A. M. and Chamorro, L. P.

"AN EXPERIMENTAL STUDY ON THE EFFECTS OF WINGLETS ON THE WAKE AND PERFORMANCE OF A MODEL WIND TURBINE"

Energies, Vol. 8, October 2015, pp. 11955-11972.

Wind tunnel experiments were performed to investigate the effects of downstream-facing winglets on the wake dynamics, power and thrust of a model wind turbine. Two similar turbines with and without winglets were operated under the same conditions. Results show an increase in the power and thrust coefficients of 8.2 percent and 15.0 percent for the wingletted case. A simple theoretical treatment of a two-turbine system suggests a possible positive tradeoff between increasing power and thrust coefficients at a wind farm scale. The higher thrust coefficient created a region of enhanced mean shear and turbulence in the outer portion of the wake. The winglets did not significantly change the tip-vortex strength, but higher levels of turbulence in the far wake decreased the tip-vortex strength. Because of the increased mean shear in the wingletted turbine's wake, the Reynolds stresses were higher, potentially leading to a higher energy flux downstream.

Tobin, N., Hamed, A. M. and Chamorro, L. P.

"EXPERIMENTAL STUDY OF THE EFFECTS OF WINGLETS ON THE WAKE OF A MODEL WIND TURBINE"

APS Division of Fluid Dynamics, Abstract D28.002, November 2015, Boston, MA.

Wind tunnel particle image velocimetry was used to investigate the effects of winglets on the wake dynamics of a model wind turbine. The behavior of a turbine with downstream-facing winglets was compared with a turbine without winglets. The turbines were placed in a turbulent boundary layer that reached up to the hub height, allowing for investigation of behavior in both turbulent and uniform flow. The winglets did not significantly change the strength of the tip vortices in the region of uniform flow. The tip vortices in the more turbulent region, however, decayed much faster, diminishing to near-zero within the first about 1.5 rotor diameters, whereas the upper tip vortices persisted potentially up to about 4 rotor diameters. The winglets also increased the power coefficient by 7.5 percent, while increasing the coefficient of thrust by 10.0 percent. The higher coefficient of thrust created a region of enhanced mean shear in the outer portion of the wake, leading to increased turbulence statistics in the far wake. The wingletted turbine had a similar wake deficit at 5 rotor diameters as the base turbine did at 1.5 rotor diameters, with potential implications for using wingletted turbines in wind farms.

Tolhurst, Jr., W. H.

"AN INVESTIGATION OF THE DOWNWASH AND WAKE BEHIND LARGE-SCALE SWEEPED AND UNSWEEPED WINGS"

NACA RM-A7L05, February 1948, Langley Aeronautical Lab., Langley Field, VA

A wind-tunnel investigation has been conducted to determine, at large scale, the downwash angles, dynamic pressure loss, and wake width behind wings having sweep angles of plus/minus 45 degrees, plus/minus 30 degrees, and 0 degree. Data were obtained in a vertical transverse plane located at the probable tail position behind the wings for a region from the plane of symmetry to 0.7 semispan. The results of this investigation indicate that the spanwise distribution of downwash was affected by sweep in a manner like span loading, increased toward the root by sweepforward and toward the tip by sweepback. After the first appearance of stall the downwash near the root of the swept-forward wing decreased markedly, probably because of loss of lift, while the downwash near the root of the swept-back wing increased, probably because of inboard movement of the tip vortices. Sweep in the wing plan form modified the spanwise variation of wake thickness producing a thick wake near the root of swept-forward wings and near the tip of swept-back wings. At moderate to high angles of attack, sweep tends to keep the wake high.

Tomassian, J. D.

"THE MOTION OF A VORTEX PAIR IN A STRATIFIED MEDIUM"

Ph.D. Thesis, 1979, UCLA, Los Angeles, CA

An experiment was constructed to simulate and study the motion of a vortex pair in a stratified atmosphere. The vortex trajectories indicate that the pair initially accelerates and its separation decreases when stratification is dominating, in agreement with Crow's theoretical predictions. However, a short time later, the speed of the pair decreases and its separation increases in the stratified as well as the unstratified cases. A peak in the trajectories is observed to occur at an Nt of 2.4 for all Nb/V , in agreement with observations from real aircraft. The increase in separation is caused by turbulence, and the data agree with recent numerical computations of vortex pair trajectories in a stratified medium with turbulence. As stratification is increased, the separation and the speed of the pair decreases relative to the unstratified case due to counter-sign vorticity at the boundary of the recirculation cell. The vortex pair was unstable even though the tank geometry suppressed the long wave Crow mutual induction instability. The instability disappeared and the lifetime of the pair increased when one vortex interacted with its image across a rigid boundary, indicating a short-wave antisymmetric mode as the mechanism of instability. Core radii appear to be comparable to those of real aircraft. The reduced core size in the image plane experiments is due to the low levels of turbulence which results in reduced mixing.

Tomaszewski, J. M., Lundquist, J. K., Churchfield, M. J. and Moriarty, P. J.

"DO WIND TURBINES POSE ROLL HAZARDS TO LIGHT AIRCRAFT?"

18th Conference on Aviation, Range, and Aerospace Meteorology, January 2017, Seattle, WA.

Wind energy development has increased rapidly to now account for 4.7 percent of all electricity generation in the United States. Much of this development has occurred in rural locations, where open

spaces are also home to numerous local or 'general aviation' airports. Almost 40 percent of all wind turbines in the US exist within 10 km of a small airport. Wind turbines generate electricity by extracting momentum from the atmosphere, thereby creating wakes characterized by a wind-speed deficit and increased turbulence downwind. Recently, the concern that wind turbine wakes pose hazards for small aircraft has been used to limit wind farm development; however, conflicting estimates on the extent of the wake's hazardous influence still exist. As such, we use large-eddy simulations to examine the wake of a single turbine to assess hazards to small aircraft. Atmospheric measures of rotation (e.g. vorticity) were first examined, followed by wind-generated lift forces and subsequent rolling moments on hypothetical aircraft transecting the wake. Stable, unstable, and neutral cases are explored, with preliminary findings of the neutral case showing that discernible wake characteristics diminish by 10 rotor diameters downstream, and over 99.99 percent of rolling moments experienced by hypothetical planes during through-wake transects are classified as a 'low' roll hazard.

Tomaszewski, J. M., Lundquist, J. K., Churchfield, M. J. and Moriarty, P. J.

"DO WIND TURBINES POSE ROLL HAZARDS TO LIGHT AIRCRAFT?"

Wind Energy Science, Vol. 3, 2018, pp. 833-843.

Wind energy accounted for 5.6% of all electricity generation in the United States in 2016. Much of this development has occurred in rural locations, where open spaces favorable for harnessing wind also serve general aviation airports. As such, nearly 40% of all United States wind turbines exist within 10 km of a small airport. Wind turbines generate electricity by extracting momentum from the atmosphere, creating downwind wakes characterized by wind-speed deficits and increased turbulence. Recently, the concern that turbine wakes pose hazards for small aircraft has been used to limit wind-farm development. Herein, we assess roll hazards to small aircraft using large-eddy simulations (LES) of a utility-scale turbine wake. Wind-generated lift forces and subsequent rolling moments are calculated for hypothetical aircraft transecting the wake in various orientations. Stably and neutrally stratified cases are explored, with the stable case presenting a possible worse-case scenario due to longer-lasting wakes permitted by lower ambient turbulence. In both cases, only 0.001% of rolling moments experienced by hypothetical aircraft during down-wake and cross-wake transects lead to an increased risk of rolling.

Tombach, I. H.

"INFLUENCE OF METEOROLOGICAL FACTORS ON THE VORTEX WAKE OF A LIGHT, TWIN-ENGINE AIRCRAFT"

AFOSR-74-1507, March 1974, AeroVironment Inc., Pasadena, C.

The smoke-marked trailing vortex wake generated by a light, twin-engine aircraft (Aero Commander 560F) was probed by another instrumented aircraft and the velocity and temperature fields in the wake were measured. Ground-based cameras recorded overall wake motion and decay due to instabilities. It was determined that wakes descending in a stably stratified atmosphere acquire buoyancy and then

subsequently begin to lose it before they break up. The speed of descent of the wakes decreases with time, and the vortex spacing and the size of the buoyant oval both increase very slightly as the wake descends. A clear correlation between wake tilting and wind shear has been established, and it was determined that shear is one factor which causes the sometimes-observed single persistent vortex.

Tombach, I. H.

"MEASUREMENTS OF THE BEHAVIOR OF VORTEX WAKES OF AIR FORCE TACTICAL AIRCRAFT"

AV FR 654, June 1976, AeroVironment Inc., Pasadena, CA

The velocity fields induced by the trailing vortices generated by T-38, F-4, and A-7 aircraft flying over a 4-meter-high anemometer array were recorded. A total of 163 tests were flown, which encompassed both normal approach and holding configurations of the aircraft. Meteorological conditions were measured simultaneously for correlation with the velocity measurements.

Tombach, I. H.

"TRANSPORT OF A VORTEX WAKE IN A STABLY STRATIFIED ATMOSPHERE"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971, pp. 41-56

Atmospheric stratification affects the downward motion of an aircraft vortex wake and influences the persistence and stability of the vortex pair configuration. Observations of actual wakes have shown significant variation in the distance to which they descend and in their lifetimes under different degrees of atmospheric stability. This behavior has been modeled analytically as a pair of infinite vortices in an inviscid, compressible, stably stratified atmosphere with entrainment characterized by a single parameter which is related to the difference between the density in a particular region of the wake and that external to the wake. It has been found that the motion of such a vortex system is governed by a parameter Q which depends on the initial circulation and vortex spacing, on the atmospheric stability, and on the entrainment parameter.

Tombach, I. H.

"TRANSPORT AND STABILITY OF A VORTEX WAKE"

MRI 72 FR-1010, April 1972, Meteorology Research Inc., Altadena, CA.

The influence of the atmospheric environment on the transport and decay of a trailing vortex wake has been studied. An analytic model describing the descending motion of an entraining wake in a stably stratified atmosphere has been developed. This model was compared with several other recent theoretical analyses and with limited experimental observations in order to determine the validity.

Tombach, I. H.

"OBSERVATIONS OF ATMOSPHERIC EFFECTS ON VORTEX WAKE BEHAVIOR"

J. Aircraft, Vol. 10, No. 11, November 1973, pp. 641-647

Smoke-marked trailing vortices were generated by a light aircraft under a hierarchy of measured atmospheric stability and turbulence levels and their motion and decay was recorded photographically. Decay from both sinuous vortex interaction and core bursting type instabilities occurred, with bursting being the dominant mode. Turbulence had a strong effect on wake life, with time-to-breakup for both modes varying as $\epsilon^{-1/3}$ to the $1/3$ power, where ϵ is the turbulent dissipation rate. Observed lifetimes ranged from 6 sec in light-to-moderate turbulence to more than 80 sec in calm, stable air. One exceptionally long-lived solitary vortex was observed for more than 3 min. Atmospheric stratification had a weak influence on wake life and its effect on wake descent could not be determined, since descent was often stopped by a rolling of the plane of the vortices. The observed data correlates well with a new theory for time-to-breakup.

Tombach, I. H.

"THE EFFECTS OF ATMOSPHERIC STABILITY, TURBULENCE AND WIND SHEAR ON AIRCRAFT WAKE BEHAVIOR"

Proceedings of the Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorology Society, 1974, pp. 405-41.

The properties of a smoke-marked wake from a light, twin-engine aircraft were measured experimentally. Correlations were made between wake motion and size and the atmospheric factors of wind, stability, turbulence, and wind shear.

Tombach, I. H. and Bate, Jr., E. R.

"STUDY OF THE MOTION AND PROPERTIES OF THE VORTEX WAKE OF A LIGHT TWIN-ENGINE AIRCRAFT"

AV FR-351, September 1973, AeroVironment Inc., Pasadena, CA.

The smoke-marked trailing vortex wake generated by a light twin-engine aircraft (Aero Commander 560F) was probed by another instrumented aircraft and the velocity and temperature fields in the wake were measured. Ground-based cameras recorded overall wake motion and decay due to instabilities. It was determined that wakes descending in a stably stratified atmosphere acquire buoyancy and then subsequently begin to lose it. The speed of descent of the wakes decreases slightly, and the vortex spacing and the size of the buoyant oval both increase as the wake descends. The tangential velocity around the vortices also decreases slightly as the wake ages. From the various observations it is concluded that representation of wake behavior in terms of an inviscid stage, an entraining stage, and a decaying stage is valid and useful. An experiment was performed to evaluate the effect of the motion of a wing-mounted drag-flap on vortex instabilities. The flap was found to affect vortex-behavior, but a complete assessment of its effectiveness will require further tests.

Tombach, I. H., Bate, Jr., E. R. and MacCready, Jr., P. B.

"INVESTIGATION OF THE MOTION AND DECAY OF THE VORTEX WAKE OF A LIGHT TWIN-ENGINE AIRCRAFT"

AV-FR-439, October 1974, AeroVironment Inc., Pasadena, CA

The properties of the smoke-marked trailing vortex wake generated by a light, twin-engine aircraft (Aerocommander 560F) were investigated experimentally. Velocity and temperature fields in the wake were measured by another instrumented probe aircraft. Ground-based and airborne cameras recorded the motion and decay of the smoke-marked vortices. A clear correlation between wake tilting and wind shear transverse to the wake was observed. The measured descent speed of wakes decreased with time in a stable atmosphere, and the spacing between the vortex pair and the size of the buoyant wake oval both increased slightly as the wake descended. Termination of the organized motion in the wakes was always brought about by vortex instabilities, with vortex breakdown (bursting) predominating for the aircraft scale and flight conditions investigated.

Tombach, I. H., Crow, S. C. and Bate, Jr., E. R.

"INVESTIGATION OF VORTEX WAKE STABILITY NEAR THE GROUND"

AFOSR TR-75-1501, July 1975, AeroVironment Inc., Pasadena, CA

The sinuous mutual induction instability of a vortex pair has been investigated theoretically and experimentally in atmospheric conditions which prevail near the aground. Two theoretical models were developed - one for a vortex pair in the constant stress layer of the atmospheric boundary layer, and the second for a vortex interacting with its image when in ground effect. The theoretical results show that the proximity of the ground shortens wake lifetime by up to 10% compared to the results aloft. The experimental data agrees satisfactorily with the theoretical predictions.

Tombach, I. H., Lissaman, P. B. S. and Mullen, J. B.

"AIRCRAFT VORTEX WAKE BEHAVIOR AND DECAY NEAR THE GROUND"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 297-309

One of the apparent modes of decay of aircraft wake vortices has been variously described as vortex breakdown or vortex bursting, the latter because of the visual appearance of this decay mode when the vortices are marked with smoke. A multi-faceted experimental and analytical research program was carried out to explore the details of vortex breakdown under conditions representative of those which would prevail at low altitudes in the vicinity of airports. Three separate approaches were taken simultaneously. Flight tests with Lockheed L-18 Lodestar and Boeing 747 aircraft flying over an array of ground-based cameras and instrumentation provided data on overall vortex behavior, on the vortex

ages at the time of onset of instabilities, and on the changes in the vortex velocity fields which resulted from vortex breakdowns. Analytical work on stability theories identified conditions under which vortices could undergo unstable decay. Experimental tests in a water tank looked at the internal instability of vortices, and also shed light on vortex motion near the ground. Finally, a heuristic modeling approach consolidated the results of these programs into a simple representation of the relationship between the times of vortex breakdowns and the ambient turbulence levels.

Tombach, I. H., Lissaman, P. B. S., Mullen, J. B. and Barker, S. J.

"AIRCRAFT VORTEX WAKE DECAY NEAR THE GROUND"

FAA-RD-77-46, May 1977, AeroVironment Inc., Pasadena, CA

A multi-faceted experimental and analytical research program was carried out to explore the details of aircraft wake vortex breakdown under conditions representative of those which would prevail at low altitudes in the vicinity of airports. Three separate approaches were taken simultaneously. Flight tests with Lockheed L-18 Lodestar and Boeing 747 aircraft flying over ground-based instrumentation provided data on overall vortex behavior, on the vortex ages at the time of onset of instabilities and on the changes in the vortex velocity fields which resulted from vortex breakdowns. Analytical work on stability theories identified conditions under which vortices could undergo unstable decay. Experimental tests in a water tank looked at the internal instability of vortices, and also shed light on vortex motion near the ground. Finally, a heuristic modeling approach resulted in a simple representation of the relationship between the times of vortex breakdowns and the ambient turbulence levels.

Tong, W., Chowdhury, S., Zhang, J. and Messac, A.

"IMPACT OF DIFFERENT WAKE MODELS ON THE ESTIMATION OF WIND FARM POWER GENERATION"

AIAA Paper 2012-5430, September 2012, Indianapolis, Indiana.

The power generation of a wind farm is significantly less than the summation of the power generated by each turbine when operating as a standalone entity. This power reduction can be attributed to the energy loss due to the wake effects -- the resulting velocity deficit in the wind downstream of a turbine. In the case of wind farm design, the wake losses are generally quantified using wake models. The effectiveness of wind farm design (seeking to maximize the farm output) therefore depends on the accuracy and the reliability of the wake models. This paper compares the impact of the following four analytical wake models on the wind farm power generation: (i) the Jensen model, (ii) the Larson model, (iii) the Frandsen model, and (iv) the Ishihara model. The sensitivity of this impact to the Land Area per Turbine and the incoming wind speed is also investigated. The wind farm power generation model used in this paper is adopted from the Unrestricted Wind Farm Layout Optimization methodology. Single wake case studies show that the velocity deficit and the wake diameter estimated by the different analytical wake models can be significantly different. A maximum difference of 70 percent was also observed for the wind farm capacity factor values estimated using different wake models.

Tophoj, L. and Aref, H.

"CHAOTIC SCATTERING OF TWO IDENTICAL POINT VORTEX PAIRS REVISITED"

Physics of Fluids, Vol. 20, 2008, pp. 093605-1 - 093605-10.

A new numerical exploration suggests that the motion of two vortex pairs, with constituent vortices all the same absolute circulation, displays chaotic scattering regimes. The mechanisms leading to chaotic scattering are different from the slingshot effect identified by Price and occur in a different region of the four-vortex phase space. They may, in many cases, be understood by appealing to the solutions of the three-vortex problem obtained by merging two like-signed vortices into one of twice the strength and by assuming that the four-vortex problem has unstable periodic solutions like those seen in the thereby associated three-vortex problems. The integrals of motion, linear impulse and Hamiltonian are recast in a form appropriate for vortex pair scattering interactions that provides constraints on the parameters characterizing the outgoing vortex pairs in terms of the initial conditions.

Toratani, D. and Itoh, E.

"MERGING OPTIMIZATION METHOD CONSIDERING MINIMUM TIME SEPARATION BASED ON WAKE VORTEX CATEGORY"

AIAA Paper 2018-1596, January 2018, Kissimmee, FL.

To advance air traffic control, the merging optimization method has been studied. This method simultaneously optimizes the trajectory and sequence of the arrival aircraft while maintaining a sufficient time separation at the merging point to avoid wake turbulence. In this study, the minimum time separation based on the wake turbulence category is applied to the merging optimization method. The separation standards are stipulated by the wake turbulence category based on the sizes of the leading and following aircraft. Considering the wake turbulence category is one of the key techniques for implementing the merging optimization method in practical air traffic control. Numerical simulations are performed to show the validity of the proposed method. The simulation results are compared with those of the merging optimization method with a specified sequence to review the optimality of the proposed method. The simulation results show that the merging optimization method can optimize the merging trajectories considering the minimum time separation based on the wake turbulence category.

Torralba, M. A., Cerezo, J., Claverias, S., Reyes, M., Climent, H., Suner, C. and Karpel, M.

"WAKE VORTEX ENCOUNTER LOADS. FLIGHT TESTS AND NUMERICAL SIMULATIONS"

ICAS 2014, September 2014, St. Petersburg, Russia.

The paper will present the wake vortex encounter (WVE) problem from a dynamic loads standpoint. The numerical simulation methodology and assumptions for loads calculation will be explained, as well

as the models and tools used for that purpose. An extensive Flight Test campaign has been dedicated to study the phenomenon and validate the overall loads calculation process. Some parametric studies, devoted to a better understanding of the phenomenon and its sensitivities to some geometrical parameters will also be presented. Finally, a stochastic approach to the loads calculation has been performed to link the loads levels with their probabilities. This kind of approach will permit to assess the definition of wake vortex scenarios for future regulations.

Toubin, H., Bailly, D. and Costes, M.

"IMPROVED UNSTEADY FAR-FIELD DRAG BREAKDOWN METHOD AND APPLICATION TO COMPLEX CASES"

AIAA Journal, Vol. 54, No. 6, June 2016, pp. 1907-1921.

Far-field drag extraction has the advantage over near-field integration of providing a phenomenological breakdown of drag. A decomposition into components linked to shock waves, viscous interactions, and lift-induced vortices is straightforward for steady flows. A formulation based on thermodynamic considerations is used at ONERA - The French Aerospace Lab and by its partners, but it is restricted to steady cases. A generalization to unsteady flows of the Van der Vooren formulation has been developed and tested on three unsteady cases previously. The proposed method allowed the breakdown of drag into the three usual components only; however, the induced drag coefficient remained ill-defined. This unsteady formulation is here modified to better express the induced drag. A new drag component is identified as a propagation and acoustic contribution. The new formulation is then applied to complex cases: two-dimensional and three-dimensional pitching cases, and an OAT15A profile subject to buffet simulated by zonal detached-eddy simulation computations.

Tracy, P. W. and Berger, J. H.

"THE EFFECTS OF INSTALLING VORTEX ATTENUATING DEVICES ON THE DESIGN, PERFORMANCE, AND OPERATIONS OF A HEAVY COMMERCIAL JET TRANSPORT"

D6-34174, October 1975, Boeing Commercial Airplane Company, Seattle, W.

The effect of two trailing vortex attenuation concepts on the design, performance, and operations of an existing heavy jet transport have been investigated. The two concepts studied are the trailing-edge spline and high thrust on the outboard engines. Losses in takeoff, landing, and mission performance, along with potential operational problems, have been identified and feasibility recommendations have been made.

Traub, L. W.

"EFFECTS OF TAPER RATIO ON TRAILING VORTEX STRUCTURE"

Aero. J., Vol. 100, No. 996, June/July 1996, pp. 252-254

A theoretical study was undertaken to determine the effect of taper ratio on the trailing vortex structure of a high aspect ratio unswept wing. The wing was modelled using lifting line theory, and the vortex was assumed to have a Rankine distribution of circulation. The results show that reducing the taper ratio of the wing decreases the maximum tangential velocity of the vortex as well as the vortex span while the core's diameter increases. Data is also presented showing the sensitivity of induced drag to wake vortex parameters.

Traub, L. W. and Agarwal, G.

"AERODYNAMIC CHARACTERISTICS OF A GURNEY/JET FLAP AT LOW REYNOLDS NUMBERS"

J. Aircraft, Vol. 45, No. 2, March-April 2008, pp. 424-429

A low-speed wind-tunnel investigation has been undertaken to establish the effect of a Gurney flap used in conjunction with a jet flap at low Reynolds numbers. The characteristics of the combination were explored as a potential control effector for small unmanned aerial vehicles. Measurements included force balance, wake survey, and flow visualization. The results indicate that the jet flap maintains a theoretically determined dependence on the jet momentum coefficient, even at a low Reynolds number (160,000). A numerical lifting-line program was modified to allow estimate of the rolling moment that may be generated by ailerons composed of a Gurney/jet flap. The numerical data suggest that the jet flap can generate significant rolling moments with realistic jet momentum coefficients.

Traub, L. W. and Nurick, A.

"EFFECTS OF WING-TIP VORTEX FLAPS"

J. Aircraft, Vol. 30, No. 4, July-August 1993, pp. 557-560

The trailing vortex system of a finite lifting wing induces a downwash, and consequently a rotation of the freestream velocity vector giving rise to vortex drag. The importance of wing tip geometry in the generation of vortex drag has propagated several tip-mounted drag reducing devices aimed at improving wing efficiency. Successful concepts include winglets and tip sails.

Traub, L. W., Mani, S., Galls, S. F. and Rediniotis, O. K.

"APPLICATION OF THE VORTEX BREAKDOWN PHENOMENON IN THE ATTENUATION OF TRAILING VORTICES"

Aeronautical Journal, Vol. 102, No. 1018, October-December 1998, pp. 439-444

An experimental investigation to determine the effectiveness of a wing-tip device designed to attenuate the trailing vortex of a lifting, flat-plate wing is detailed. The induced-breakdown vortex

attenuation device (IBVAD) is essentially a toed-in, vertically-oriented sheared tip. Results are presented comprising force-balance, water tunnel flow visualization, and wake studies using a seven-hole probe. The data show that compared with an equal-span rectangular wing, variations of the IBVAD device can reduce drag at moderate-to-high lift coefficients, as well as reduce the maximum rotary velocity of the trailing vortex by 28 percent. Axial vorticity in the wake vortex was significantly attenuated compared with the rectangular wing, with a 52.6 percent reduction in the magnitude of the maximum vorticity. The vortex core radius was also seen to be larger than the rectangular wing. However, even substantial attenuation and redistribution of trailing vorticity may be insufficient to reduce the wake hazard.

Traugott, S. C.

"INTERNAL GRAVITY WAVE GENERATION BY VORTEX WAKES"

AFOSR-TR-77-1309, December 1977, Martin Marietta Corp., Baltimore, MD.

The investigation focused on various details relating to the numerical prediction of vortex wakes. Contributions are described to the reduction of false transport effects and the prediction of the descent velocity of an unsteady, viscous strongly interacting vortex distribution.

Traugott, S. C.

"VISCOUS DECAY OF A TWO-DIMENSIONAL INTERACTING VORTEX PAIR"

Bull. Am. Physical Society, Vol. 20, No. 11, November 1975, p. 1428

The far downstream stage of decay of a stable vortex wake behind an aircraft is simulated by a rectilinear counter-rotating vortex pair. A numerical finite difference calculation is used to follow the evolution of an initially prescribed vorticity distribution under the action of viscosity. The initial vorticity distribution is not concentrated in cores but is continuously distributed according to an analytical steady inviscid solution which represents the two-dimensional analog of Hill's spherical vortex. There is initially no jump in vorticity at the boundary between inner and outer flow, and the numerical results then describe distortion and decay as the vortices annihilate each other.

Trayford, R. S. and Welch, L. W.

"AERIAL SPRAYING: A SIMULATION OF FACTORS INFLUENCING THE DISTRIBUTION AND RECOVERY OF LIQUID DROPLETS"

Journal of Agricultural Engineering Research, Vol. 22, Issue 2, June 1977, pp. 183-196.

A computer model has been developed and used to assess the effects of wing tip vortices, crosswind, height, evaporation, and propeller swirl on the trajectories of droplets emitted from an agricultural

aircraft. The ground deposits resulting from the simulation suggest restraints on the design of an aircraft nozzle layout. The results and their method of presentation are discussed.

Trieling, R. R., Dam, C. E. C. and van Heijst, G. J. F.

"DYNAMICS OF TWO IDENTICAL VORTICES IN LINEAR SHEAR"

Physics of Fluids, Vol. 22, 2010, pp. 117104-1 - 117104-13.

The dynamics of two identical vortices in linear shear was studied both numerically and experimentally. Numerical simulations based on the technique of contour dynamics reveal that the vortex evolution in adverse shear is significantly different from that in cooperative shear. Vortices in adverse shear predominantly separate, whereas vortices in cooperative shear predominantly merge. In addition, adverse shear may destruct the vortices much in the same way as a single vortex in adverse shear, whereas cooperative shear stabilizes the vortices and thus enhances the possibility of vortex merger. The critical distance for vortex merger depends strongly on both the sign and the

Trieling, R. R., Fuentes, O. U. V. and van Heijst, G. J. F.

"INTERACTION OF TWO UNEQUAL COROTATING VORTICES"

Physics of Fluids, Vol. 17, 2005, 087103-1 to 087103-17

Previous high-resolution contour dynamics calculations [Dritschell and Waugh, Phys. Fluids A 4, 1737 (1992)] have shown that in two-dimensional inviscid flow the interaction of two unequal corotating vortices with uniform vorticity is not always associated with vortex growth and may lead to vortices smaller than the original vortices. In the present study, we investigate whether these results also hold for two-dimensional vortices with continuous vorticity distributions. Similar flow regimes are found as for uniform vorticity patches, but the variation of the flow regimes with the initial vortex radii and peak vortices is more complicated and strongly dependent on the initial shape of the vorticity profile. It is found that the 'halo' of low-value vorticity, which surrounds the cores of continuous vortices, significantly increases the critical distance at which the weaker vortex is destroyed. The halo also promotes the vortex cores to merge more efficiently, since it accounts for a substantial part of the loss of circulation into filaments. Simple transformation rules and merger criteria are derived for the inviscid interaction between two Gaussian vortices. The strong dependence of the flow regimes on the initial vorticity distribution partly explains why previous laboratory experiments in an electron plasma [Mitchell and Driscoll, Phys. Fluids 8, 1828 (1996)] show complete merger of two unequal vortices in a range of parameter space where contour dynamics simulations with uniform vorticity patches predict partial merger or partial straining-out of the smaller vortex. It is shown that the measured times for complete merger are in reasonable agreement with inviscid dynamics when the vortices are very similar. For more distinct vortices the weaker vortex is often observed to be destroyed on a time scale much smaller than expected from inviscid numerical simulations. An explanation for this discrepancy is given by the combined effects of vortex stripping and viscous diffusion, which leads to an enhanced

erosion of the weaker vortex. These results are verified by laboratory experiments in a conventional (rotating) fluid.

Trier, S. B.

"MODELING STUDIES OF TURBULENCE MECHANISMS ASSOCIATED WITH MESOSCALE CONVECTIVE SYSTEMS"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 17, 2016, Springer International Publishing Switzerland, pp. 335-356.

High-resolution numerical simulations have aided recent understanding of mechanisms responsible for convectively induced aviation turbulence (CIT) spatially removed from its parent moist convection. Anticyclonic jets occurring near the tropopause, which are often significantly enhanced by mesoscale convective systems or other forms of organized convection, influence a variety of different mechanisms of turbulence at commercial aviation cruising altitudes. Herein, we describe different CIT mechanisms that are possible near these anticyclonic outflow jets and illustrate them with examples from recent simulations.

Trigub, V. N., Blokhin, A. B. and Simakin, I. N.

"THE ASYMPTOTIC STUDY OF DISSIPATION AND BREAKDOWN OF A WING-TIP VORTEX"

J. Fluid Mech., Vol. 274, 1994, pp. 293-337

The steady axisymmetrical wing-tip vortex is studied in this paper by means of asymptotic methods within the limit of high Reynolds numbers. The smooth regrouping of the vortex under the action of viscous forces is described by a quasi-cylindrical approximation. The solutions of the quasi-cylindrical approximation are thoroughly analyzed numerically and it is shown that a saddle-point bifurcation appears at certain critical values of circulation. At these values the solution may be continued in two ways: as a supercritical branch which approaches the Batchelor limit far downstream; and a subcritical one, which passes the second, nodal-point bifurcation. The parabolic quasi-cylindrical equations past this point allow the downstream disturbances to propagate upstream, like for example, boundary-layer equations in the regime of strong hypersonic interaction. The flow past the second bifurcation point was studied numerically and it was shown that solutions of the quasi-cylindrical approximation with large reversed-flow regions exist. An asymptotic expansion of such solutions far downstream was constructed, and it turned out that the reversed-flow region expands exponentially. This process is halted by elliptical effects in the external flow. An asymptotic theory of large reversed-flow regions is suggested including viscosity and elliptical effects. Numerical solutions for unbounded vortex breakdown parabolically expanding far downstream are presented. Then the general asymptotic problem statement which describes the flow near the bifurcation points is used to study the asymptotic solutions near the first bifurcation point. The problem is investigated numerically and two kinds of solution, which may be treated as transcritical jumps and marginal vortex breakdown, are found and discussed.

Tritschler, J. K., Celi, R. and Leishman, J. G.

"METHODOLOGY FOR ROTORCRAFT BROWNOUT MITIGATION THROUGH FLIGHT PATH OPTIMIZATION"

Journal of Guidance, Control and Dynamics, Vol. 37, No. 5, September-October 2014, pp. 1524-1538.

A methodology is presented for the selection of approach-to-landing maneuvers that may result in improved brownout characteristics. The methodology is based upon a brownout metric that assesses the relative brownout cloud volume densities in critical regions of the pilot's field of view. The metric becomes the objective function of a procedure in which a typical visual approach profile is parameterized and optimized to minimize brownout in a representative landing maneuver. The optimization is constrained to avoid maneuvers that would be conducive to the onset of vortex ring state or would result in flight within the 'avoid' regions of a typical helicopter height-velocity diagram. The analysis uses a free-vortex wake model and simulates the dynamics of the dust particles immersed in the rotor downwash. The results show that the optimal approach trajectories affect the resulting flowfield, particularly the development of a ground vortex ahead of the rotor disk, which influences the rate of development, size, and volume density of the brownout cloud. The results are compared with prior experimental results, and potential operational interpretations of the outcomes are examined.

Trokhimovski, Y. G., Westwater, E. R., Han, Y. and Leuski, V. Y.

"AIR AND SEA SURFACE TEMPERATURE MEASUREMENTS USING A 60-GHZ MICROWAVE ROTATING RADIOMETER"

IEEE Transactions on Geoscience and Remote Sensing, Vol. 36, No. 1, January 1998, pp. 3-15.

Data obtained from a single-channel scanning 5-mm radiometer on a research vessel were used for the study of sea surface temperature and lower-atmospheric temperature profiles under neutral, weakly stable, and unstable conditions. Comparisons with in situ air and water temperature measurements, dropsonde temperature data, radiosonde data, and VV Ku-band side-looking radar images are presented. The technique based on 5-mm measurements determines the air-skin water (skin depth of 0.3 mm) temperature difference with an accuracy of the order of 0.1 K. Analysis of the experimental data suggests that the air-skin water temperature difference depends weakly on solar heating and wind speed V for $2.5 < V < 9$ m/s.

Troldborg, N., Zahle, F., Rethore, P.-E. and Sorensen, N. N.

"COMPARISON OF THE WAKE OF DIFFERENT TYPES OF WIND TURBINE CFD MODELS"

AIAA Paper No. 2012-0237, January 2012, Nashville, TN.

The wake of the NREL 5MW wind turbine was simulated using CFD with a fully resolved rotor geometry, an actuator line method and actuator disc method, respectively. Simulations were carried out prescribing both uniform and turbulent inflow and the wake properties predicted by the three models were compared. The actuator disc and line methods were in very close agreement for uniform inflow using RANS, whereas the gradients were smeared more rapidly in the fully resolved rotor wake. In uniform inflow using DES the fully resolved rotor wake broke up approximately 1D downstream, where the actuator disc and line wakes remained stable. In the simulations with turbulent inflow the wakes behind the actuator line and fully resolved rotor were in very close agreement, indicating that the differences observed in uniform inflow do not play an important role if the inflow is turbulent.

Tromer, O., Schroder, W. and Meinke, M.

"NUMERICAL SIMULATION OF NORMAL- AND OBLIQUE-SHOCK VORTEX INTENSITIES"

Journal of Applied Mathematics & Mechanics, Vol. 80, Supplement 1, 2000, pp. S181-S182.

The dependence of the breakdown topology on the shock-vortex interaction conditions is numerically investigated. Based on solutions of the Euler equations the unsteady three-dimensional flow field is studied at several freestream Mach numbers and for normal and oblique shocks. The results of the finite-volume method using the AUSM approach indicate a strong dependence of the recirculation region downstream of the shock on the shock induced pressure gradient and on the vortex strength.

Troncoso, F. M. and Feldman, A. B.

"WAKE TURBULENCE AND THE JUMBO JETS - WHOSE RESPONSIBILITY, PILOT OR CONTROLLER"

Annals of Air and Space Law, Vol. 3, 1978, pp. 269-28.

Case law regarding the wake turbulence danger for small aircraft operating near jumbo jets is reviewed. One of the questions arising in the cases studied is whether the controller has a duty to provide wake turbulence warnings, or whether it is the pilot's duty to avoid the vortices. A finding of wake turbulence does not necessarily mean that the Government bears responsibility for negligence; the determination of duty and proximate cause is essential to the resolution of the cases.

Tropea, C., Nobach, H., Ramond, A. and Reulet, P.

"TURBULENT VELOCITY SPECTRA FROM LASER DOPPLER DATA"

3rd ONERA-DLR Aerospace Symposium, June 2001, Paris, pp. S4-3/1-13.

This contribution reviews the estimation of spectra from laser Doppler data and provides some recommended guidelines. It is shown that reliable spectral estimates can be achieved for frequencies well beyond the mean data rate. The estimators discussed here exhibit some further advantages when used for processing data from multi-point measurements, used for spatial correlations. Some final remarks are directed towards the ramifications of these procedures on the optical system design.

Tsirkunov, Y. M., Lobanova, M. A., Tsvetkov, A. I. and Schepanyuk, B. A.

"LARGE-SCALE VORTEX STRUCTURE OF FLOW IN THE NEAR WAKE BEHIND AN AIRLINER DURING TAKEOFF AND LANDING"

ICAS-2016-0666, September 2016, Daejeon, Korea.

The large-scale flow vortex structure in the near-field wake of airliner moving on the runway during its takeoff and landing was investigated numerically based on a RANS approach with the SST turbulence model using ANSYS soft. Numerical results are compared with the ones obtained earlier for a cruising flight, and they are added by experimental data in the wind tunnel.

Tsirkunov, Yu. M., Lobanova, M. A., Tsvetkov, A. I. and Schepanyuk, B. A.

"EFFECT OF THE WING TRAILING-EDGE FLAPS AND SPOILERS POSITION ON THE JET-VORTEX WAKE BEHIND AN AIRCRAFT DURING TAKEOFF AND LANDING RUN"

7th European Conference for Aeronautics and Space Sciences (EUCASS 2017), July 2017, Milan, Italy.

The large-scale vortex structure of flow in the near wake behind an aircraft during its run on a runway is investigated numerically. The geometrical aircraft configuration was taken close to a mid-range commercial aircraft like Boeing 737-300. It included all essential elements: a body (fuselage), wings with winglets, horizontal and vertical stabilizers, engine nacelles, nacelle pylons, inboard flap track fairings, leading-edge and trailing-edge flaps, and spoilers. Flaps and spoilers position corresponded to the takeoff and landing run condition. Computational simulation was based on solving the Reynolds averaged Navier-Stokes equations closed with the Menter SST turbulence model. Patterns of streamlines, fields of the axial vorticity and the turbulent intensity, vertical and horizontal velocity profiles in the wake are compared and discussed for both run regimes. The flow model was preliminary tested for validity by comparison of the calculated velocity profiles behind a small-scaled aircraft model with those obtained in special wind tunnel experiments.

Tsutomi, T., Kazuhiko, K., Hiromachi, O. and Yasuaki, M.

"FLOW VISUALIZATION ABOUT WAKE VORTEX CAVITATION WITH PIV SYSTEM"

Nihon Kikai Gakkai Nenji Taikai Koen Ronbunshu, Vol. 2, 2001, pp. 255-256 (In Japanese).

It is well known that the regular vortex shedding process named Karman vortex streets always occurs in the wake behind bluff bodies under high Reynolds number. The wake flow with cavitation has the same process and the Strouhal number depends on the cavitation number. But, the interference mechanism between the vortex shedding process and cavitation scale has not been clarified. This study investigated the flow visualization about wake vortex cavitation behind a wedge at several cavitation numbers by using PIV and LDV systems. The vortex shedding process had two modes corresponding to

the cavitation number. To examine this mechanism, the flow visualization was executed by using the method which lays the vector map on top of the image map.

Tucker, H. G.

"DIRECTIONAL ANEMOMETER FOR NEAR-GROUND AIRCRAFT VORTEX WAKE DETECTION"

National Research Council Canada Bulletin, Vol. 8, No. 2, July 1976

The Control Systems and Human Engineering Laboratory in the Division of Mechanical Engineering is currently developing a specialized anemometer which is based on the deflection of a turbulent air jet and is capable of simultaneously measuring the direction and mean magnitude of the horizontal wind velocity component as well as the fluctuations of the vertical wind velocity component. This instrument has potential application in increasing the utilization rate of airfield landing strips by detecting and monitoring vortex wakes generated during landings and take-offs. In particular, the instrument may be readily designed to exceed the reliability, sensitivity and dynamic response requirements while being cost effective relative to other anemometers of at least comparable performance.

Tucker, V. A.

"GLIDING BIRDS: REDUCTION OF INDUCED DRAG BY WING TIP SLOTS BETWEEN THE PRIMARY FEATHERS"

Journal of Experimental Biology, Vol. 180, July 1993, pp. 285-310.

The feathers at the wing tips of most birds that soar over land separate both horizontally and vertically in flight to form slotted tips. The individual feathers in the slotted tips resemble the winglets used on the wing tips of some aircraft to reduce induced drag. A wing that produces lift leaves a pair of vortex sheets in its wake. Wing theory shows that winglets can reduce the kinetic energy left in the vortex sheets, and hence the induced drag, by spreading vorticity both horizontally and vertically. This paper describes the aerodynamic forces on a wing made of a base wing and different wing tips. The feathered wing tip was slotted and was made of four primary feathers from a Harris' hawk (*Parabuteo unicinctus*). The Clark Y tip was unslotted and was made of balsa wood shaped to a Clark Y airfoil. The balsa feather tip was slotted and was made of three balsa wood wings shaped like feathers.

Tuerk, L., Coors, D. and Jacob, D.

"BEHAVIOR OF WAKE VORTICES NEAR THE GROUND OVER A LARGE RANGE OF REYNOLDS NUMBERS"

Aerospace Science and Tech., Vol. 3, No. 2, February 1999, pp. 71-81

Recent numerical simulations of the wake vortex behavior close to the ground cover a Reynolds number range that is far below the realistic value of 10×10^7 - 10×10^8 . Therefore, one goal of the study was the expansion of the range of simulated cases to Reynolds numbers up to 3.33×10^6 . Another goal was the prediction of the maximum altitude the vortices reach during and after their various rebounds. It is shown that the strength of the wake vortex flow behind large aircraft is not reduced by the wake vortex ground interaction and that the vortex aging is extremely slow, at least if a laminar and two-dimensional flow is assumed. The high Reynolds number wakes of big aircraft show a conservation of the primary vortex circulation and a negligible growth rate of the vortex core radii.

Tulin, M. P. and Schwartz, J.

"THE MOTION OF TURBULENT VORTEX-PAIRS IN HOMOGENEOUS AND DENSITY STRATIFIED MEDIA"

TR-231-15, April 1971, Hydronautics Inc., Laurel, MD

A theory for the motion of two-dimensional turbulent vortex pairs in homogeneous media has been developed based on separate velocity scaling of the internal and external flow fields involved in the motion and considering variations in volume, circulation, momentum, and energy. Based on the results obtained from this theory a simplified theory is derived to deal with the rising motion of turbulent vortex pairs in stratified media. The theoretical results are compared with systematic experimental observations.

Tung, C. and Lim, J.

"ANALYSIS OF ROTOR VORTREX WAKE STRUCTURE USING 3-C PIV MEASUREMENTS"

In Vortex Dominated Flows, edited by D. Blackmore, E. Krause and C. Tung, 2005, World Scientific, New Jersey, Chapter 13, pp. 229-249.

Three-component (3-C) PIV measurements of a model rotor wake in descent flight are analyzed. The measuring PIV plane is always cutting the vortex with an angle. Another difficulty is the convective velocity of the vortex wake is not known accurately either. The measured vortex wake geometry has been used to determine the convection velocity. For three closely adjacent points along the curved vortex, one may fit a circular arc. The orientation of the PIV measuring plane to the plane that is normal to the curved vortex at the middle point can be easily determined by the geometry of these three points. Both vortex core radius and peak swirl velocity are smaller in the resolved normal plane than the one obtained in the measuring plane. Vortex formation, structure and decay are also discussed.

Tung, C., Gallman, J. M., Kube, R., Wagner, W., Van der Wall, B., Brooks, T. F., Burley, C. L., Boyd Jr., D. D., Rahier, G. and Beaumier, P.

"PREDICTION AND MEASUREMENT OF BLADE-VORTEX INTERACTION LOADING"

1st Joint CEAS/AIAA Aeroacoustics Conf., June 1995, Munich, Germany.

An extensive quantity of airload measurements was obtained for a pressure-instrumented model of the BO-105 main rotor for many higher-harmonic control settings at Duits-Nederlandse Wind Tunnel. The wake geometry, vortex strength, and vortex core size were also measured through a laser light sheet technique and LDV. These results are used to verify the BVI airload prediction methodologies developed by AFDD, DLR, NASA Langley, and ONERA. The comparisons show that an accurate prediction of the blade motion and the wake geometry is the most important aspect of the BVI airload predictions.

Tung, C., Pucci, S. L., Caradonna, F. X. and Morse, H. A.

"THE STRUCTURE OF TRAILING VORTICES GENERATED BY MODEL ROTOR BLADES"

Vertica, Vol. 7, No. 1, 1983, pp. 33-43

The present study is one of a series of tests employing hot-wire anemometry to investigate the effects of blade geometry on vortex structure. These tests cover a range of aspect ratios and blade twist. For all configurations, measured vortex strength correlates well with maximum blade-bound circulation. Measurements of wake geometry agree with classical data for high aspect ratios. The detailed vortex structure is like that found for fixed wings and consists of four well-defined regions - a viscous core, a turbulent mixing region, a merging region, and an inviscid outer region. All high aspect ratio data are described by a single set of empirical formulas.

Tung, C., Russell, J. W. and Sankar, L. N.

"MODIFICATIONS OF THE TIP VORTEX STRUCTURE FROM A HOVERING ROTOR USING SPOILERS"

IUTAM Symposium on Dynamics of Slender Vortices, Aachen, Germany, August 31-September 3, 1997

Numerical studies of the tip vortex structure from a hovering rotor with and without various spoilers are presented. A general multizone unsteady three-dimensional Navier-Stokes solver is developed to determine the flowfield. A scheme that is fifth-order accurate in space and first-order accurate in time is used to improve the capturing of the tip vortex. Velocity data from the core of the vortex is studied at various planes behind the blade trailing edge. Computations of this velocity data for a clean rotor are first compared with experimental results obtained for the same rotor test case. Three different trailing edge spoiler configurations are then investigated to see if the tip vortex structure can be favorably altered.

Tung, C., Yu, Y. H. and Low, S. L.

"AERODYNAMIC ASPECTS OF BLADE-VORTEX INTERACTION (BVI)"

AIAA Paper No. 1996-2010, New Orleans, June 199.

This paper presents a review of the blade-vortex interaction (BVI) phenomenon. Both analytical and experimental studies of two-dimensional parallel airfoil-vortex interaction, three-dimensional BVIs, and helicopter rotor BVIs are covered. The important parameters that affect the BVI airloads are discussed.

Tur, A. and Yanovsky, V.

"POINT VORTICES WITH A RATIONAL NECKLACE: NEW EXACT STATIONARY SOLUTIONS OF THE TWO-DIMENSIONAL EULER EQUATION"

Physics of Fluids, Vol. 16, No. 8, August 2004, pp. 2877-2885

In this paper we find a new class of explicit exact stationary solutions of the two-dimensional (2D) Euler equation which describe vortex patterns of necklace type with $N + 1$ -fold symmetry in rotational shear flow. The point vortex with a strength equal to plus/minus $4\pi N$ (where N -integer number) is situated in the center of the vortex structure. The vorticity distribution outside of the center is smooth and is described by a two-parametric family of rational functions which are known in explicit form for any N . In the centers of vortex satellites the vorticity does not have any singularity and remains of finite value. When N is increasing, the solutions describe the transition layer in 2D-rotational shear flow.

Turchak, L. I.

"VORTEX SAFETY IN AVIATION"

Application of Mathematics in Technical and Natural Sciences, AIP Conference Proceedings 1487, 2012, pp. 49-62.

The objective is the general review of impact of aircraft wake vortices on the follower aircraft encountering the wake. Currently, the presence of wake vortices past aircraft limits the airspace capacity and flight safety level for aircraft of different purposes. However, wake vortex nature and evolution have not been studied in full measure. A mathematical model simulating the process of near wake generation past bodies of different shapes, as well as the wake evolution after rolling-up into wake vortices (far wake) is developed. The processes are suggested to be modeled by means of the Method of Discrete Vortices. Far wake evolution is determined by its complex interaction with the atmosphere and ground boundary layer. The main factors that should be considered are: wind and ambient turbulence 3D-distributions, temperature stratification of the atmosphere, wind shear, as well as some others which effects will be manifested as considerable during the investigation. The ground boundary layer effects on wake vortex evolution are substantial at low flight altitudes and are determined through the boundary layer separation.

Turkgeldi, I. E. and Kandil, O. A.

"DEVELOPMENT AND APPLICATION OF ADAPTIVE DYNAMIC GRID FOR WAKE-VORTEX/GROUND INTERACTION"

AIAA Paper No. 2000-0789, Reno, NV, January 2000.

An adaptive dynamic grid method for wake vortex/ground interaction problems is developed and its effects on the solution accuracy have been investigated. The unsteady full Navier-Stokes equations are solved by using three different grids. The first grid is a single-zone and fixed-size grid. The second grid is also a single-zone grid but its fine core region is split into two parts whenever the separation distance of the vortices exceeds a certain length. The third grid uses a multizone technique by means of two embedded grids placed at vortex cores to alleviate excess numerical dissipation. These grids are applied to the same initial-condition case with a linear crosswind shear and a prescribed temperature distribution due to the engine exhaust plume. The results are compared with the measurements taken at Idaho Falls in 1990. It has been conclusively demonstrated that an adaptive dynamic grid combined with a multizone approach is necessary to obtain accurate results.

Turner, G. P., Padfield, G. D. and Harris, M.

"ENCOUNTERS WITH AIRCRAFT VORTEX WAKES: THE IMPACT ON HELICOPTER HANDLING QUALITIES"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 839-849

A study concerning the risks associated with locating a helicopter final approach and takeoff area alongside an active runway at a busy international airport is documented. Specifically, using desktop simulation, the problem is addressed of an in-flight helicopter encountering the shed wing tip vortex from a large transport aircraft. Measurements are reviewed of vortices taken using coherent laser radar equipment located under the final approach path to London Heathrow Airport to establish a model of the vortex velocity profile. The simulations have shown the helicopter can experience transient pitch attitude changes of up to 40 deg and accumulated descent rates of 1500 ft/min (457 m/min) during the encounter, assuming that no pilot intervention is made. Established handling qualities metrics have been adapted and suggest that these responses may produce handling difficulties. The simulations were also broadened to consider a range of helicopter designs and the effects of shed vortices from a number of large transport aircraft. It is concluded that under particular circumstances a helicopter can experience significant transient motions on encountering a shed wing tip vortex, although no attempt has been made to estimate the probability of this occurrence.

Turner, H. L.

"MEASUREMENT OF THE MOMENTS OF INERTIA OF AN AIRPLANE BY A SIMPLIFIED METHOD"

NACA Technical Note No. 2201, October 1950, Ames Aeronautical Lab., Moffett Field, CA.

A simplified method for the experimental determination of the moments of inertia, product of inertia, and inclination of the principal axes; the associated equipment and techniques; and the application of this method to a conventional 13,000-pound airplane are described. Measurements were made with the landing gear retracted for full and empty fuel conditions. The equipment, which consisted primarily of knife-edge supports and restraining springs for the pitch and roll axes and a single-shaft torsional pendulum for the yaw axis, was designed for increased accuracy as well as for simplicity of operation

and ease of handling as compared with previous methods. At no time was it necessary to hoist or jack the airplane in an abnormal fashion.

Turner, J.

"ETWIRL - A EUROPEAN WAKE VORTEX INCIDENT REPORTING SYSTEM AND DATABASE"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 119-123.

ETWIRL (European Turbulent Wake Incident Reporting Log) is a European Commission funded project to establish a pan-European wake vortex incident reporting system and database. The database will hold details of actual incidents and associated meteorological data for use in model validation, safety studies and by aviation organizations worldwide. The project is being implemented jointly by the UK Met. Office and RED Scientific Ltd. At this stage, the database contents and products have still to be finalized, subject to users' requirements.

Turner, J.

"ETWIRL: A NEW PAN-EUROPEAN WAKE VORTEX REPORTING SYSTEM AND DATABASE"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998.

Increasing demands on European airport capacity has recently brought the issue of wake vortex hazards to the forefront of aviation research. However, current wake vortex separation rules take no account of the effects of meteorological conditions. With sufficient understanding of these effects, the potential to decrease separations under favorable meteorological conditions could be realized without compromising safety standards. The European Commission has recently contracted with aviation specialists RED Scientific Ltd. along with the UK Met. Office to implement a Europe-wide wake vortex incident reporting system, utilizing both automatic and human data sources. The project, named ETWIRL (European Turbulent Wake Incident Reporting Log), will run for two years, and will develop a database of wake vortex encounters at European terminals along with comprehensive meteorological data. This paper describes the expected content of the database together with a discussion about potential methods of data dissemination to interested parties. Confidentiality issues and the future role of the database will also be discussed.

Turner, J.

"DEVELOPMENT OF A WAKE VORTEX INCIDENT REPORTING SYSTEM AND DATABASE"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 571-581

In planning for increased capacity in aviation transport in the next century, changes in procedure must be based not only on the results of research, but on a sound assessment of current practices.

There is currently no source of objective and comprehensive data on wake vortex incidents which may be used in safety assessments and research. The European Turbulent Wake Incident Reporting Log is a European Commission funded project to establish a pan-European wake vortex incident reporting system and database. The database will hold details of actual incidents and associated meteorological data for use in model validation, safety studies and by aviation organizations worldwide. At this stage, the database contents and products have still to be finalized, subject to users' requirements. An Internet site has been launched inviting feedback from all parties on the database content and proposed products.

Turner, J. A., Halsey, N. G. J. and Cole, G.

"A EUROPEAN WAKE VORTEX ENCOUNTER REPORTING SYSTEM AND DATABASE"

Proceedings of the 8th Conference on Aviation, Range, and Aerospace Meteorology, Dallas, TX, January 1999

In response to the growing pressure of increased air traffic on terminal capacity, changes in wake vortex separation procedures must be based not only on the results of theoretical research, but on a sound assessment of current practices. Hence there is a requirement for an objective system for recording wake vortex encounters and the conditions leading to them. ETWIRL (European Turbulent Wake Incident Reporting Log) is a European project to establish a fully comprehensive pan-European wake vortex incident reporting system and database. The database holds details of actual incidents and associated meteorological data for use in model validation, safety studies and by aviation organizations worldwide. The reporting system began operations in early 1998, and data became available to aviation organizations and researchers during summer 1998. The system currently involves the participation of several major European airlines and air traffic services. The success of the project so far has generated much interest in the US, and it is hoped that a similar system could be implemented to address the increasing capacity problem at many US airports.

Turner, J. S.

"A COMPARISON BETWEEN BUOYANT VORTEX RINGS AND VORTEX PAIRS"

J. Fluid Mech., Vol. 7, June 1960, pp. 419-432

In this paper it is shown how earlier results for buoyant vortex rings may be extended to describe the corresponding two-dimensional case, which arises in the theory of bent-over plumes. It is again assumed that in uniform surroundings the circulation remains constant while the buoyancy acts to increase the momentum of the pair. The behavior in two dimensions is quite different from that in three, however; a buoyant vortex ring spreads linearly with height, whereas a buoyant pair spreads exponentially with height, or linearly with time (and therefore, in a bent-over plume, linearly with distance downward). The theory has been extended to describe the rise of buoyant rings and pairs through stably stratified surroundings having a linear density gradient. The behavior near the maximum height reached is found to depend critically in both cases on the relative rates at which the

circulation and the momentum fall to zero. If these reach zero together, the rings or pairs will steadily increase in size and come to rest at a finite height and with a finite radius. If the circulation is non-zero when the momentum vanishes, the radius begins to decrease soon after the buoyancy becomes zero, and the vortices will therefore tend to break up suddenly and mix into their surroundings. There is a considerable increase in the final height which should be attained by vortex rings or bent-over plumes if the initial circulation is increased; it is suggested that releasing smoke intermittently, rather than continuously, at high velocity might be a means of increasing the effective height of chimneys in calm conditions. When the circulation reaches zero before the momentum does, the solutions indicate that the radius becomes very large near the level of zero buoyancy.

Turner, J. S.

"BUOYANT VORTEX RINGS"

Proc. Royal Soc. London A, Mat. 239, 1957, pp. 61-75

It is pointed out that there is a fundamental difference in the behavior of vortex rings projected upwards, according as they do or do not contain fluid which is lighter than the surroundings. A theory based on the perfect fluid approximation is developed to describe the motion of buoyant rings in a uniform fluid. The essential assumption is that the circulation remains constant with time while the buoyancy force acts to increase the impulse of a ring. This leads to the prediction that increasing the buoyancy will give a greater rate of expansion and a lower velocity of rise. The theory is extended to the case of a ring rising through a stably stratified fluid having a constant density gradient; in this case increasing the buoyancy should lead to a lower final height. The predictions of the theory have been verified by carrying out experiments in the laboratory with small vortex rings formed in water, using methylated spirits and salt to produce the density differences. The observations suggest that substantially the same analysis may be applicable to phenomena on a larger scale in the atmosphere; the velocity and final height of an explosion cloud should be determined by the buoyancy and circulation generated near the ground and the stability conditions of the atmosphere.

Tymczyszyn, J. J.

"SUMMARY OF PANEL STATEMENT REGARDING WAKE TURBULENCE"

FAA Symposium on Turbulence, Federal Aviation Administration, Washington, DC, March 1971, p. 21

The highlights of the Wake Turbulence Program at Edwards Air Force Base, Seattle, and Idaho Falls were presented. The principal results included: that flap extension on the generating airplane always resulted in a reduction of apparent vortex strength and persistence, the influence of span ratios of the following aircraft was dominant, and that general aviation airplanes sometimes experienced violent vertical acceleration at distances greater than that which would produce uncontrollable roll.

Tymczyszyn, J. J. and Barber, M. R.

"RECENT WAKE TURBULENCE FLIGHT TEST PROGRAMS"

Soc. Exp. Test Pilots 1974 Report to the Aerospace Profession, Eighteenth Symposium Proceedings, Vol. 12, No. 2, 1974, pp. 52-67

The introduction of wide-bodied jumbo jet transports into commercial and military service in the last 5 years has prompted four major wake vortex flight tests which involved having various instrumented probe aircraft fly behind jumbo jets. The early test programs, which were conducted by NASA/FAA/USAF/industry/airline teams, were intended primarily to determine separation distance requirements. More recently they have also been made to demonstrate the potential of wake vortex alleviation configurations. These tests were made using the B-747 airplane.

Tymczyszyn, J. J. and Barber, M. R.

"TECHNIQUES FOR EARLY DEMISE OF VORTICES - A PILOT'S VIEW"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 247-263.

The emphasis on full-scale airborne flight testing of wake vortex turbulence has naturally phased into a systematic evaluation of methods for attenuating vortex strength rather than concentrating primarily on the basic consideration of determining separation distances required for safe control of the following aircraft. A brief review of several techniques is provided with emphasis on the most successful configuration explored to date. This configuration change has been the extension of the two most outboard spoiler segments during the landing approach of the B-747. Similar configurations have been successfully tested in wind tunnels by NASA-LRC for the DC-10 and L-1011 and flight tests of the L-1011 are scheduled for the immediate future. An attempt is made to predict the operational environmental and certification problems which would have to be considered if reduced spacing is dictated by the need to improve airport capacity and general arguments are presented in favor of wake vortex alleviation.

Tymczyszyn, J. J., Biehl, K. J. and Teager, S. A.

"FLIGHT TEST INVESTIGATION OF THE WAKE VORTICES GENERATED BY ROTORCRAFT"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 13-1 - 13-27

Helicopter wake vortices were probed by small airplanes to obtain a direct assessment of vortex hazard as a function of distance behind the generating helicopter. These tests were designed to provide data for establishing Air Traffic Control separation criteria and for comparison with theoretical calculations. The obvious lack of flight test measurements of helicopter wake turbulence prompted the FAA to undertake a helicopter wake turbulence program in the late 1980's. The result was a flight test program that was a combination of ground based and airborne experimentation, though only the airborne results are presented here. This study is especially timely due to the preponderance of

theoretical calculations based on ground tests that preceded these flights. These ground-based tests suggest a high wake vortex hazard from rotorcraft and consequently imply large separation distances for safe IFR flight behind rotorcraft.

Uberoi, M.

"MECHANISMS OF DECAY OF LAMINAR AND TURBULENT VORTICES"

Project SQUID Technical Report UC-1-PU, Purdue University, December 1977

Dynamics of an infinitely long one-dimensional vortex and a swirl are compared with dynamics of a semi-infinitely long trailing vortex and trailing swirl. With increasing distance, the change in axial velocity difference between the core of the trailing vortex and the surrounding region causes radial convection and some associated axial convection of angular momentum. In laminar or turbulent trailing vortices, this is the dominant mechanism for decrease in velocities of swirl in the core and corresponding growth of the core. Axial velocity difference between the core of the trailing vortex and the surrounding region is necessary for the sustenance of turbulence in the vortex core. A theory of turbulent trailing vortex is developed based on these mechanisms and the results are compared with experimental observations.

Uberoi, M. S.

"MECHANISMS OF DECAY OF LAMINAR AND TURBULENT VORTICES"

J. Fluid Mech., Vol. 90, Part 2, 1979, pp. 241-256

The dynamics of an infinitely long one-dimensional vortex and a swirl are compared with the dynamics of a semi-infinitely long trailing vortex and trailing swirl. With increasing distance, the change in the axial velocity difference between the core of the trailing vortex and the surrounding region causes radial convection and some associated axial convection of angular momentum. In laminar or turbulent trailing vortices, we show that under most conditions of interest this is the dominant mechanism for the decrease in the velocities of swirl in the core and corresponding growth of the core. Based on theoretical considerations and experimental observations, we show that the axial velocity difference between the core of the trailing vortex and the surrounding region is necessary for the sustenance of turbulence in the vortex core. A theory of the turbulent trailing vortex is developed based on these mechanisms and the results are compared with our experimental observations.

Uberoi, M., Shivamoggi, B. K. and Chen, S.-S.

"AXIAL FLOW IN TRAILING LINE VORTICES"

Project SQUID Technical Report UC-2-PU, Purdue University, June 1978

Axial flow in the core of laminar steady trailing vortex from the tip of a semi-infinite lifting wing is analyzed, assuming that the pressure gradient is determined by the swirl velocities of an ideal infinite

line vortex. The axial and lateral variations of the axial velocity depend on the strength of the vortex and initial axial velocity distribution which must be specified at some station behind the wing.

Uhlman Jr, J. S.

"AN INTEGRAL EQUATION FORMULATION OF THE EQUATIONS OF MOTION OF AN INCOMPRESSIBLE FLUID"

TR 10,086, July 1992, Naval Undersea Warfare Center, Newport, RI.

A set of coupled integral equations is derived from the incompressible Navier-Stokes equations and the continuity equation. These equations are based on a vorticity-velocity-enthalpy formulation and are exact. The equations consist of a generalization of the Biot-Savart law for determining the velocity, an integral expression of the momentum equation for determining the vorticity, and a boundary integral equation for determining the stagnation enthalpy. The equations are linear in each independent variable, with the nonlinearities entering only through the cross terms of the vorticity and velocity. They possess several interesting properties, including the total absence of spatial derivatives and the fact that the stagnation enthalpy, or pressure, is required only on the boundary of the fluid domain. In addition, since the vorticity is present in all volume integrals, the domain of integration in this case is restricted to the region of nonzero vorticity. All boundary conditions, and particularly the far field boundary condition, are naturally incorporated in the formulation.

Uhlman, J., Grant, J., Fine, N. and Rees, F.

"ON THE SOUND GENERATED BY AIRCRAFT TRAILING VORTICES: A DESCRIPTION OF THE PROJECT SOCRATES THEORY AND MODELING EFFORT"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998

Results are presented of the Project SOCRATES Theory and Modeling study concerning the acoustic signature of aircraft wake vortices. The paper, which is an account of a work in progress, will focus on the examination of the physical mechanisms responsible for low frequency vortex-generated sound using a combination of analytical, computational, and experimental methods. A Lagrangian vorticity collocation method is used to compute the dynamics of columnar trailing vortices and Powell's form of Lighthill's acoustic analogy is used to compute the resulting sound field. Analytical results for a few canonical problems, such as the sound radiated by small amplitude core vibrations of infinite columnar vortices and vortex rings, are used to validate the numerical calculation of the acoustic field. Results of computational simulations will be shown for several model problems. Of particular interest for the wake-vortex problem is the sound field radiated by columnar vortices with periodic wrapped vortex rings which are known to form when strong coherent vortex structures interact with the relatively weak small-scale structures embedded in the ambient turbulence. That interaction is expected to be a dominant sound radiating mechanism for trailing wake vortices. Computational and measured sound field characteristics will be compared in an attempt to support or refute that supposition.

Ulken, R.

"INVESTIGATION OF WAKE VORTICES OF LANDING AIRCRAFT AT FRANKFURT AIRPORT"

DFVLR MITT-88-15, May 1988, DFVLR, Braunschweig, Germany

At Frankfurt Airport investigations of wake vortices were carried out. It should be discovered whether and under which meteorological conditions landing aircraft could be endangered by wake vortices generated by leading large transport aircraft on a parallel glide path. The crosswind shows an evident influence on the horizontal motion of a vortex. But its velocity during 56% of the time of the main air traffic is so slow that a vortex cannot reach the parallel glide path with dangerous intensity due to its limited life-span. Within the remaining time the danger to a following aircraft depends very strongly on the meteorological conditions of the vicinity.

Unterstrasser, S.

"LARGE-EDDY SIMULATION STUDY OF CONTRAIL MICROPHYSICS AND GEOMETRY DURING THE VORTEX PHASE AND CONSEQUENCES ON CONTRAIL-TO-CIRRUS TRANSITION"

Journal of Geophysical Research: Atmospheres, Vol. 119, 2014, pp. 7537-7555.

Large-eddy simulations with Lagrangian ice microphysics were used to study the early contrail evolution during the vortex phase. Micro physical and geometrical properties of a contrail produced by a large-sized aircraft (type B777/A340) were investigated systematically for a large parameter range. Crystal loss due to adiabatic heating in the downward moving vortices was found to depend strongly on relative humidity and temperature, qualitatively like previous 2-D simulation results. Contrail depth is as large as 450 m for the investigated parameter range and was found to be underestimated in a previous 2-D study. Further sensitivity studies show a nonnegligible effect of the initial ice crystal size distribution and the initial ice crystal number on the crystal loss, whereas the contrail structure and ice mass evolution is only barely affected by these variations. Variation of fuel flow has the smallest effect on crystal loss. At high supersaturations, our choice of contrail spatial initialization may underestimate the ice crystal loss. The set of presented sensitivity studies is a first step toward a quantitative description of young contrails in terms of vertical extent and crystal loss. Concluding contrail-to-cirrus simulations demonstrate the relevance of vortex phase processes and its three-dimensional modeling on the later contrail-cirrus properties.

Unterstrasser, S. and Solch, L.

"STUDY OF CONTRAIL MICROPHYSICS IN THE VORTEX PHASE WITH A LAGRANGIAN PARTICLE TRACKING MODEL"

Atmos. Chem. and Physics, Vol. 10, 2010, pp. 10003-10015.

Crystal sublimation/loss is a dominant feature of the contrail evolution during the vortex phase and has a substantial impact on the later contrail-to-cirrus transition. Previous studies showed that the fraction of crystals surviving the vortex phase depends primarily on relative humidity, temperature, and

the aircraft type. An existing model for contrail vortex phase simulations (with a 2-moment bulk microphysics scheme) was upgraded with a newly developed state-of-the-art microphysics module (LCM) which uses Lagrangian particle tracking. This allows for explicit process-oriented modeling of the ice crystal size distribution in contrast to the bulk approach. We show that it is of great importance to employ an advanced microphysics scheme to determine the crystal loss during the vortex phase. The LCM-model shows even larger sensitivities to the above-mentioned key parameters than previously estimated with the bulk model. The impact of the initial crystal number is studied and for the first time also the initial width of the crystal size distribution. Both are shown to be relevant. This corroborates the need for a realistic representation of microphysical processes and knowledge of the ice phase characteristics.

Unterstrasser, S. and Stephan A.

"FAR FIELD WAKE VORTEX EVOLUTION OF TWO AIRCRAFT FORMATION FLIGHT AND IMPLICATIONS ON YOUNG CONTRAILS"

The Aeronautical Journal, Vol. 124, No. 1275, May 2020, pp. 667-702.

Large-eddy simulations (LES) have been employed to investigate the far-field four-vortex wake vortex evolution over 10min behind an aircraft formation. In formation flight scenarios, the wake vortex behavior was found to be much more complex, chaotic, and diverse than in the classical single aircraft case, depending very sensitively on the formation geometry, i.e. the lateral and vertical offset of the two involved aircraft. Even though the case-by-case variability of the wake vortex behavior across the various formation flight scenarios is large, the final plume dimensions after vortex dissolution are in general substantially different from those of single aircraft scenarios. The plumes are around 170 to 250m deep and 400m to 680m broad, whereas a single A350/B777 aircraft would produce a 480m deep and 330m broad plume. Formation flight plumes are thus not as deep, yet they are broader, as the vortices do not only propagate vertically but also in span-wise direction. Two different LES models have been employed independently and show consistent results suggesting the robustness of the findings. Notably, CO₂ emissions are only one contribution to the aviation climate impact among several others like contrails and emission of water vapor and nitrogen oxides, which would be all affected by the implementation of formation flight. Thus, we also highlight the differences in ice microphysical and geometrical properties of young formation flight contrails relative to the classical single aircraft case.

Unterstrasser, S., Gierens, K. and Spichtinger, P.

"THE EVOLUTION OF CONTRAIL MICROPHYSICS IN THE VORTEX PHASE"

Meteorologische Zeitschrift, Vol. 17, No., April 2008, pp. 145-156.

We investigate the evolution of contrails during the vortex phase using numerical simulations. Emphasis is placed on microphysical properties and on the vertical distribution of ice mass and number concentration at the end of the vortex phase. Instead of using a 3D model which would be preferable

but computationally too costly, we use a 2D model equipped with a special tool for controlling vortex decay. We conduct a great number of sensitivity studies for one aircraft type. It turns out that atmospheric parameters, namely supersaturation, temperature, stability and turbulence level have the biggest impact on the number of ice crystals and on the ice mass that survives until vortex breakup and that therefore makes up the persistent contrail in supersaturated air. The initial ice crystal number density and its distribution in the vortex, are of minor importance.

Unterstrasser, S., Paoli, R., Solch, I., Kuhnlein, C. and Gerz, T.

"DIMENSION OF AIRCRAFT EXHAUST PLUMES AT CRUISE CONDITIONS: EFFECT OF WAKE VORTICES"

Atmospheric Chemistry and Physics, Vol. 14, 2014, pp. 2713-2733.

The dispersion of aircraft emissions during the vortex phase is studied using a 3-D LES model with Lagrangian particle tracking. The simulations start with a fully rolled-up vortex pair of a type B747/A340 airplane and the tracer centered around the vortex cores. The tracer dilution and plume extent is studied for a variety of ambient and aircraft parameters until aircraft-induced effects have ceased. For typical upper tropospheric conditions, the impact of stratification is more dominant compared to turbulence intensity or vertical wind shear. Moreover, the sensitivity to the initial tracer distribution was found to be weak. Along the transverse direction, the tracer concentration can be well approximated by a Gaussian distribution, along the vertical a superposition of three Gaussian distributions is adequate. For the studied parameter range, the vertical plume expansion ranges from 400 m to 500 m and cross-sectional area from 40,000 square meters to 60,000 square meters after six minutes. for validation, selected simulations were compared to an alternative LES model and to in-situ NO-measurements.

Urech, A., Ballesteros, L., Perez, D. and Garcia, L.

"THE CREDOS PROJECT: MADRID BARAJAS CASE STUDY"

D5-7, December 2009.

This report is aimed at analyzing CREDOS Concept implementation in Madrid Barajas airport (LEMD), with reliable and real data as far as possible taking the current level of development of the project, through expert experience, fast time simulations and data offered from other similar studies. This deliverable provides a specific case study of the CREDOS implementation from the point of view of Operation, Human Factor and Cost Benefit Analysis. The Operational study analyses the scenario at LEMD, including current traffic, wind, and operational restrictions. A set of Fast Time Simulations were performed to provide an estimation of the improvement in reduction of delay that the use of CREDOS separations could bring to Madris-Barajas. The main conclusion is that current traffic figures do not account for a large improvement due to CREDOS as the target runway is not saturated, although the reduction of delay during peak periods could be enough to justify its implementation. The methodology used in the case study is summarized to serve as guidelines for other possible case studies of the implementation of CREDOS at other airports who would wish to follow.

Uzel, J. N. and Marchman, III, J. F.

"THE EFFECT OF WING-TIP MODIFICATIONS ON AIRCRAFT WAKE TURBULENCE"

VPI-E-72-8, July 1972, Virginia Polytechnic Institute and State University, Blacksburg, VA

Several different wing-tip modifications were used to alter the characteristics of an airfoil trailing vortex. Preliminary photographs were taken using a tuft-grid to visually determine the effects of the various tip configurations. Detailed mean flow measurements were then made at ten and thirty chord lengths downstream of the wing. As a first approximation, the static pressure was assumed to be constant. The results show a definite decrease in the tangential velocity of the vortex and a spreading out of the core for all modifications tested.

Uzun, A. and Hussaini, M. Y.

"A COMPUTATIONAL STUDY ON TIP VORTEX NOISE"

AIAA Paper No. 2008-2913, Vancouver, Canada, May 2008

Tip vortex noise is an important component of aircraft high-lift device noise. It is imperative to gain a better understanding of this problem before appropriate noise reduction technologies can be developed and implemented effectively. This paper reports results from our ongoing work on tip vortex simulations. The simulations are performed using a high-order accurate, multi-block, large eddy simulation (LES) code with overset grid capability. The main emphasis of the present simulations is to simulate the formation of a tip vortex around a wing with a blunt tip and its interaction with the wing surface. The blunt tip geometry actually gives rise to the formation of two vortices. The primary vortex forms over the upper surface of the wing, while the secondary vortex forms off the side edge. These two vortices merge to form the tip vortex. Comparisons of the simulation results with available experimental data are shown. Some of the observed differences between the LES and the experiment are believed to be due to the Reynolds number differences between them.

Uzun, A. and Hussaini, M. Y.

"SIMULATIONS OF VORTEX FORMATION AROUND A BLUNT WING TIP"

AIAA Journal, Vol. 48, No. 6, June 2010, pp. 1221-1234.

We report our findings from a computational study on wing-tip vortices. The main emphasis of the simulations is to compute the formation of a tip vortex around a blunt wing tip and its interaction with the wing and tip side-edge surfaces. Comparisons of simulation results with available experimental data are done to assess the prediction capability of the simulations. The simulations are performed on a computational grid containing 110 million points total. The blunt tip geometry gives rise to the formation of two vortices. The primary vortex forms over the upper surface of the wing, and the secondary vortex forms off the side edge. These two vortices merge around the tip trailing edge to

form the tip vortex. Simulations at the experimental Reynolds number of 1,800,000 are performed using several sub-grid scale models. It is shown that the simulation performed without an explicit sub-grid scale model, also known as implicit large eddy simulation, produces the best agreement with the experimental measurements. Although some differences between the simulation results and experimental data still exist, the overall agreement between the experiment and simulation is found to be satisfactory.

Uzun, A., Hussaini, M. Y. and Streett, C. L.

"TOWARDS TIP VORTEX NOISE PREDICTION BY HIGH-ORDER LES ON OVERSET GRIDS"

AIAA Paper No. 2005-2865, Monterey, CA, May 2005

This paper reports on a multi-block large eddy simulation (LES) code with overset grid capability which has been developed to primarily study the tip vortex noise problem arising on rotating wind turbine blades. The LES code can also be used to simulate the tip vortices around stationary wing geometries typically found in aeronautical applications. It employs state-of-the-art compact finite differencing, implicit spatial filtering, and non-reflecting boundary conditions on free boundaries, as well as characteristic-type boundary conditions on solid walls. High-order accurate interpolation is used for the transfer of information among the individual component grids that make up the overset grid topology. The multi-block nature and the overset grid capability of the code allow high-order accurate numerical solutions in complex domains. Results for the tip vortex around a stationary wing with a rounded tip are presented to demonstrate the capability of the code. Comparisons of the numerical results with experimental data are also carried out for the validation of the computational methodology.

Uzun, A., Hussaini, M. Y. and Streett, C. L.

"LARGE-EDDY SIMULATION OF A WING TIP VORTEX ON OVERSET GRIDS"

AIAA Journal, Vol. 44, No. 6, 2006, pp. 1229-1242.

This paper reports on a multi-block large eddy simulation (LES) code with overset grid capability which has been developed to primarily study the tip vortex noise problem arising on rotating wind turbine blades. The LES code can also be used to simulate the tip vortices around stationary wing geometries typically found in aeronautical applications. It employs state-of-the-art compact finite differencing, implicit spatial filtering, and non-reflecting boundary conditions on free boundaries, as well as characteristic-type boundary conditions on solid walls. High-order accurate interpolation is used for the transfer of information among the individual component grids that make up the overset grid topology. The multi-block nature and the overset grid capability of the code allow high-order accurate numerical solutions in complex domains. Results for the tip vortex around a stationary wing with a rounded tip are presented to demonstrate the capability of the code. Comparisons of the numerical results with experimental data are also carried out for the validation of the computational methodology.

Vainchtein, D. and Mezic, I.

"CONTROL OF VORTEX PAIR USING A WEAK EXTERNAL FLOW"

Journal of Turbulence, Vol. 3, Paper 051, October 2002, pp. 1-7

The problem of controlling the position of a pair of point vortices using a strain field or the field of a single source/sink is considered using singular control methods and dynamical system perturbation theory. We show that averaging over the fast rotation of the vortices around the center of vorticity reduces the order of the system of evolution equations and allows one to achieve the desired control using a single control field.

Valla, M., Augere, B., Bailly, D., Dolfi-Bouteyre, A., Garnier, E. and Meheut, M.

"PRELIMINARY STUDY OF SINGLE PARTICLE LIDAR FOR WING WAKE SURVEY"

16th Coherent Laser Conference, June 2011, Long Beach, CA.

In this paper we assess the feasibility of an airborne lidar dedicated to wing wake survey, an application that would be of real interest for applied aerodynamics research. In flight wing wake survey could lead to non-intrusive global drag estimation under realistic conditions. Single particle coherent Doppler lidar has proved to be efficient for measurements at high altitude, and thus, seems to be a good candidate to meet this challenge. The feasibility study focused on two main issues: (1) Since wind speed is retrieved from the Doppler frequency shift of natural aerosol crossing the laser beam, the lidar introduces a bias in the measurement of the wing wake profile. (2) Since the flow to be analyzed is turbulent, we must evaluate the impact of aero optical effects upon lidar performance.

Valla, M., Dolfi-Bouteyre, A., Cariou, J. P. and Lawson, J.

"WAKE VORTEX MONITORING OF DEPARTING AIRCRAFT WITH 1.5 MICRON ALL-FIBER PULSED LIDAR"

ODAS 2007, Gottingen, Germany, Oct. 2007

A new 1.5-micron pulsed lidar using an all-fiber laser source has been developed by ONERA in cooperation with Leosphere, for wake vortex and wind field measurements. The lidar has been designed for medium range detection (50 to 400 m). This system is based on telecom fiber technology which offers low cost and reliable components. The system has been tested on an airport field and has demonstrated to be well suitable for wake vortex monitoring.

Vallespin, D., Da Ronch, A., Badcock, K. J., and Boelens, O.

"VORTICAL FLOW PREDICTION VALIDATION FOR AN UNMANNED COMBAT AIR VEHICLE MODEL"

Journal of Aircraft, Vol. 48, No. 6, November-December 2011, pp. 1948-1959.

As part of the NATO Applied Vehicle Technology 161 technical group, a study of the aerodynamic behavior of the stability and control configuration wind-tunnel model is presented. Sharp and round leading-edge versions of the model are computed. A validation of Reynolds-averaged Navier-Stokes predictions obtained using two block structured codes are made. Static cases are analyzed and compared with wind-tunnel measurements. The vortical flow features are described in detail for a range of angles of attack. The predictions are in good agreement with the experiments at low angles of attack, whereas for higher angles of incidence (greater than 15 degrees), some discrepancies are seen. A dual vortex structure is present in this region for both leading-edge configurations, resulting in highly nonlinear aerodynamic behavior.

van Baren, G. B., Speijker, L. J. P. and de Bruin, A. C.

"WAKE VORTEX SAFETY EVALUATION OF SINGLE RUNWAY APPROACHES UNDER DIFFERENT WEATHER AND OPERATIONAL CONDITIONS"

NLR-TP-2002-077, February 2002, National Aerospace Laboratory, and PSAM 6 Conf., June 2002, San Juan, PR

The steady increase in air traffic imposes a need for enhanced airport capacity, and the desire to safely reduce existing separation minima. An important capacity constraint factor is the risk imposed by wake vortices. In view of the uncertainties and the difficulties in understanding the wake vortex phenomena, a novel WAKE Vortex Induced Risk assessment (WAVIR) model has been developed to evaluate wake vortex induced risk. The probabilistic model incorporates sub-models for wake vortex evolution, wake vortex encounter, and flight path evolution, and relates the severity of wake vortex encounters to incident/accident risk probability. The model is applied to evaluate the risk related to different separation distances between aircraft landing on a single runway. An extensive initial risk assessment is carried out to evaluate the impact of weather and wind conditions and procedural aspects on incident/accident risk. The risk assessment results are compared with proposed risk requirements to assess safe and appropriate separation distances. It is shown that a reduction of the current separation minima - and consequently an increase of capacity - might be possible under most operational and weather conditions. However, it is also shown that the separation distances might need to be increased under some particular weather conditions (e.g. low atmospheric turbulence).

van Baren, G., Chalon-Morgan, C. and Treve, V.

"THE CURRENT PRACTICE OF SEPARATION DELIVERY AT MAJOR EUROPEAN AIRPORTS"

Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015), June 2015, Lisbon, Portugal.

Separation minima are or can become a key bottleneck for the runway throughput at major airports. Therefore, in the context of SESAR Project 6.8.1, EUROCONTROL is investigating concepts for flexible and dynamic use of wake turbulence separations. To successfully develop such concepts and optimize the benefits, it is important that current practices and lessons learnt from today's operations are

understood and considered. The aim of the study presented in this paper is therefore to baseline the current practices for separation delivery on final approach at major European airports. For this, site visits to European ATC units in combination with analysis of radar data have been conducted. Statistical characteristics on speed, distance and time spacing as observed in today's operations depending on e.g., airport, headwind, and distance to threshold are determined. Distance spacing close to the threshold as observed in the data satisfies the minimum radar or wake turbulence separation minima with a buffer that is on average in between 0.5 and 1.0 NM and has a standard deviation of about 0.5 NM. The mean compression of distance spacing on the last 10 NM of the final approach is approximately 1 NM. About half of this compression occurs when the leader aircraft is beyond 4 DME when aircraft adapt to their final approach speed. It is shown that there are considerable differences per airport, and this illustrates that it is important to consider local conditions in the assessment of benefits for a certain airport. Furthermore, the observed mean and variation of spacing buffers may suggest that for optimized runway throughput, new concepts should not only focus on reduction of minima but also on the management of distance spacing compression variation, e.g. better understanding and predicting aircraft speed performance, such that buffers can be optimized. The results of this study are used by SESAR and EUROCONTROL in the development of a new ATC tool to predict aircraft speed performance. This Leading Optimized Runway Delivery (LORD) tool supports Air Traffic Controllers to optimize the separation buffer and more efficiently and easily deal with the compression effect on the last part of the final approach.

van Baren, G., Speijker, L. and Frech, M.

"INCREASED ARRIVAL CAPACITY THROUGH THE USE OF THE ATC-WAKE SEPARATION MODE PLANNER"

AIAA Paper No. 2006-7745, Wichita, KS, September 2006

Today's wake vortex separation rules tend to become capacity bottlenecks at busy airports. Within the ATC-Wake project for the European Commission, an integrated Air Traffic Control (ATC) wake vortex safety and capacity system has been designed to provide the means to significantly enhance airport capacity. The system will enable Air Traffic Controllers to apply new weather based dynamic aircraft separation. One of the components of the ATC-Wake system is the Separation Mode Planner (SMP) that advises the ATC supervisor about safe and adequate separation. The SMP is used in the planning phase where weather and wake vortex forecast information is used together with aircraft separation rules to establish the arrival and/or departure sequence. Weather nowcasting and wake vortex prediction and detection information is used in the tactical phase to monitor and control safe separation. Wind forecast data along the flight path is used in the proposed methodology of the SMP to determine time frames suitable for reduced separation. Criteria on crosswind and associated safe separation minima are derived from safety assessment results. The methodology is illustrated using Nowcasting Wake Vortex Impact Variables (NOWWIV) wind forecast data and WAKE Vortex Induced Risk assessment (WAVIR) results for Single Runway Arrivals. Analysis of a crosswind climatology provides insight in the potential benefits in terms of runway throughput or delay reduction.

van Baren, G., Treve, V., Rooseleer, F., van der Geest, P. and Heesbeen, B.

"ASSESSING THE SEVERITY OF WAKE ENCOUNTERS IN VARIOUS AIRCRAFT TYPES IN PILOTED FLIGHT SIMULATIONS"

AIAA Paper 2017-1084, January 2017, Grapevine, TX.

The ICAO wake turbulence separation standards for approaching and departing aircraft are considered safe and to some extent over-conservative for certain pairs of aircraft and in certain conditions. With the need to improve efficiency and capacity at the larger busy airports, research has been ongoing to come up with concepts aiming at optimized, weather dependent and pair-wise separation minima. The safety analysis of the European pair-wise concept (RECAT-PWS-EU) as developed by EUROCONTROL Agency is based on a relative assessment using the dimensionless Roll Control Coefficient (RMC) as the metric expressing wake encounter severity. Separation design is based on the principle that the worst-case RMC value that an aircraft type is exposed to, will be less than or equal to the worst-case RMC that a smaller reference aircraft is exposed to. The applicability of this alignment principle may be limited to aircraft within a certain category, because other factors than RMC may play a role in the experienced severity for aircraft that differ significantly in size and maneuverability. With the objective to create additional assurance that the estimated severity levels at the defined separations are comparable and acceptable, EUROCONTROL, in collaboration with the Netherlands Aerospace Centre NLR have conducted a campaign with realistic piloted flight simulations in the framework of the SESAR program. A range of aircraft types has been simulated in NLR's GRACE research simulator facility. More than 700 wake encounters have been flown in realistic level flight and final approach scenarios. Pilot ratings of the severity and flight data have been analyzed in combination. The results show that the RMC is a good metric for wake encounter severity. The pilot ratings for the various aircraft types correlate well with RMC values, especially in level flight. In approach, closer to ground at around 200-100 ft, pilot rating also correlates with deviations from the stabilized approach and go-around intentions. The results support the alignment as applied in the RECAT-PWS-EU Safety Case..

van Dam, C. P.

"EFFICIENCY CHARACTERISTICS OF CRESCENT-SHAPED WINGS AND CAUDAL FINNS"

Nature, Vol. 325, January 1987, pp. 435-437.

Caudal (tail) fins of fish and aquatic mammals that cruise long distances, and wings of certain birds, often have the shape of a crescent moon. This study investigates how the crescent shape contributes to the traveling performance of these animals. A steady-flow theory that correctly models the trailing wake was used to analyze lifting surface efficiency, which is dependent on the level of induced (or vortex) drag for a given lift and span of the lifting surface. This analysis shows that backward curvature of a wing improves induced efficiency to a value greater than that of the flat untwisted wing of elliptical shape considered optimal in classical wing theory. This increase of induced efficiency results from the nonplanar trailing vortex sheet produced by the crescent-shaped wing at a given angle of attack.

van de Konijnenberg, J. A., Nielsen, A. H., Rasmussen, J. J. and Stenum, B.

"SHEAR-FLOW INSTABILITY IN A ROTATING FLUID"

J. Fluid Mechanics, Vol. 387, 1999, pp. 177-204.

The instability of a forced, circular shear layer in a rotating fluid has been studied experimentally and numerically. The experiments were performed with a shallow layer of water in a parabolic tank, in which it is possible to apply radial pumping and to model a geophysical beta-effect. A shear layer was produced by a secondary rotation of the central part of the parabolic vessel. In most experiments, the shear layer takes on the appearance of a sequence of vortices, the number of which decreases with increasing strength of the shear. A beta-effect may prevent the formation of a steady vortex chain. Continuous pumping of fluid from the periphery to the center or vice versa leads to an azimuthal velocity field corresponding to a point vortex. This azimuthal flow appears to stabilize the shear flow if it is opposite to the inner rotation, and to be destabilizing otherwise. The numerical investigations consist of the solution of the quasi-geostrophic equation in a geometry like the experimental situation and with a term modeling the experimental forcing. Though the numerical computations are based on a two-dimensional model, they capture the essential features of the instability and the resulting vortex structures.

van den Berg, L.

"TOPOLOGICAL AND NUMERICAL ASPECTS OF AXISYMMETRIC VORTEX BREAKDOWN"

M-741, December 1996, Technische Univ. Delft (Netherlands), Faculty of Aerospace Engineering, Delft, The Netherlands

The emphasis of this work lies on the topological and numerical aspects of axisymmetric vortex breakdown. First, a literature survey is given of the theoretical, experimental, and numerical results concerning breakdown that could be obtained. Furthermore, the qualitative theory of dynamical systems is applied to steady axisymmetric flows. The topology of steady viscous flows is studied based on the axisymmetric Navier-Stokes equations governing incompressible laminar flow. Special attention is given to flow patterns that are concerned with the genesis of vortex breakdown bubbles. The behavior of some physical parameters, such as the kinematic pressure, the three vorticity components and the vortex stretching and tilting terms near the breakdown bubbles is investigated. Finally, numerical calculations concerning the vortical flow in a tube with convergent-divergent dimensions are performed with the help of a Navier-Stokes/Euler code.

van der Laan, J. M.

"EXPERIMENTAL VORTEX ANALYZER"

NLR MP 82006 U, January 1982, National Aerospace Laboratory, Amsterdam, The Netherlands

A measuring system is described for detection and analyses of aircraft wake vortices in the approach zone of a runway. This system consists of propeller anemometers, a data-acquisition unit, a quick-look

monitor and a NOVA minicomputer with a real-time vortex detection program. A short description of aircraft wake vortices is also given. Some results of the measuring program are discussed. [In Dutch.]

van der Laan, J. M., van den Dam, R. F., van der Weijde, H., and Aardoom, W.

"RESULTS FROM THE RLD/NLR AIRCRAFT WAKE VORTEX MEASUREMENT PROGRAM (DATA COLLECTION PERIOD APRIL - OCTOBER 1980)"

NLR TR 81067 L, June 1981, National Aerospace Laboratory, Amsterdam, The Netherlands

The results are given of an aircraft wake vortex measurement program. A Vortex Detection System is used, based on propeller anemometers. This system as well as the vortex detection software is described. Several observed weather and vortex phenomena are discussed. Cumulative distributions of vortex residence time are given, for several combinations of aircraft and windspeeds. Some aspects of the feasibility of a Vortex Advisory System, based on a wind criterion, are discussed.

van der Meijden, B., Roling, P. and Curran, R.

"FLEXIBLE RUNWAY USE MODELING USING PAIRWISE RECAT-EU SEPARATION MINIMA"

AIAA Paper 2018-3840, June 2018, Atlanta, GA.

If we would take fuel consumption and noise annoyance into account in the runway allocation process, runway allocation can take place more efficiently, both in terms of fuel cost as well as noise annoyance. In this research, the focus is on the further development of a model to make the calculations more refined. Moreover, the improvements conducted in this research relate to the methodologies to compute the cost of the decision variables and the level of complexity of specific linear programming constraints in the optimization model. Consequently, the aim of this research is to answer the following research question: Can the performance of Standard Flex be further optimized by applying pairwise flight dependencies, while ensuring and contributing to a valid trade-off between runway capacity, noise emission, fuel burn and safety. By means of this research, the flexible runway allocation model has been improved on many aspects. The computation strategy of both objectives has moved from a reference aircraft-based computation strategy to an analysis based on each unique aircraft on its own. This refined computational approach has resulted in a better understanding and modeling strategy of the operations that take place at an airport. Finally, the implementation of RECAT-EU separation minima has resulted in a reduction of 5-10 percent in overall separation times with respect to the regular ICAO WTC strategy, based on multiple air traffic demand mixture scenarios, based on a specific demand of flights.

van der Meulen, J. P.

"WIND MEASUREMENTS: POTENTIAL WIND SPEED DERIVED FROM WIND SPEED FLUCTUATIONS MEASUREMENTS, AND THE REPRESENTATIVITY OF WIND STATIONS"

WMO Instruments and Observing Methods Reports, No. 74 (WMO/TD - No. 1028), October 2000, pp. 72.

Turbulence measurements as part of operational meteorological observations for synoptical purposes provide direct information of terrain roughness. The method using standard deviations is a simple tool for the calculation of the potential wind speed providing a higher degree of representativity.

van der Meulen, J. P.

"WAKE VORTEX INDUCED WIND MEASUREMENTS AT AIRFIELDS: - A SIMPLE ALGORITHM TO REDUCE THE VORTEX IMPACT"

WMO Instruments and Observing Methods Reports, No. 70 (WMO/TD - No. 877), May 1998, pp. 139.

The surface wind measurements at an airport is intended to provide the representative condition, particularly of 6-10 m above the runway. The sensor location is such that the site should not be by affected by the flow from buildings, etc., or by aircraft operations. In practice, the final choice of the site is a compromise of many factors and as such, the sensor location may still be at times impacted by the surrounding objects and aircraft operations. In this paper, the impact of aircraft wake turbulence on the determination of wind gust is explored. A simple algorithm to detect the artificial wind guest caused by wake vortices was implemented, and was found to improve the meteorological characterization of the wind guest.

van der Vegt, J. J. W.

"FUNDAMENTALS OF THREE-DIMENSIONAL VORTEX MOTION AROUND SOLID BODIES"

Fluid Dynamics Research, Vol. 3, Issues 1-4, Sept. 1988, pp. 179-182

An Action Principle describing the evolution of a 3-D inviscid vorticity field around a solid body is presented. This variational principle is used for the construction of a numerical algorithm. A formal solution of the inviscid vorticity transport equation is given by means of a Lie transform using a Dirac bracket and Hamiltonian functional. This solution is used in a stochastic algorithm for the simulation of the evolution of a viscous vorticity field around a body.

van der Wall, B. G.

"WIND TURBINE WAKE VORTEX INFLUENCE ON SAFETY OF SMALL ROTORCRAFT"

The Aeronautical Journal, Vol. 123, No. 1267, September 2019, pp. 1374 1395.

The wake vortex of lifting surfaces such as wind turbine blades or fixed-wing aircraft can heavily affect the blade aerodynamics of rotorcraft. Using blade element theory, the pilot control inputs required to mitigate such vortex effects are estimated and compared to the available control margin at the operating condition of interest. In contrast, when no pilot action is performed, the rotor blade flapping

caused by the vortex is evaluated and compared to available margins. It is a safety concern when the remaining margins become zero. The influence of the vortex strength, its core radius and orientation to the rotor disk are evaluated and the effect of rotor blade characteristics (Lock number, natural frequency) is investigated.

van der Wall, B. G. and Richard, H.

"ANALYSIS METHODOLOGY FOR 3C-PIV DATA OF ROTARY WING VORTICES"

Experiments in Fluids, Vol. 40, 2006, pp. 798-812

3C-PIV data from tip vortices of either fixed-wing or rotating wing experiments are challenging from an analysis point of view. Model motion, vortex wander, spurious vectors, periodic and aperiodic effects, turbulence, and other disturbing effects are all present in the data. In most cases the vortices are not measured perpendicular to their axis as well. Engineers need time-averaged properties from the vortex in the vortex axis system for a proper modeling approach within simulation codes. This article describes the methods needed to deal with all the mentioned problem areas, including the conditional averaging and rotation into the vortex axis system. The methods are validated by using numerically generated vortex vector fields, and finally applied to experimental data from a hover condition of a model rotor.

van der Wall, B. G., Burley, C. L., Yu, Y., Richard, H., Pengel, K. and Beaumier, P.

"THE HART II TEST - MEASUREMENT OF HELICOPTER ROTOR WAKES"

Aerospace Science and Tech., Vol. 8, No. 2004, pp. 273-284

A key parameter to reduce rotor noise is a wake location relative to a blade. During the data analysis in the years after the HART test of 1994 it was found that comprehensive wake data are needed to understand wake development, vortex creation and aging, their motion, and their re-development after an interaction with a rotor blade. Therefore, DLR, ONERA, NASA Langley, US Army AFDD and DNW again came together and generated a follow-on program named HART II. In this program the rotor wake was intensively measured with a novel double-stereo PIV (Particle Image Velocimetry) system. This provides instantaneous flow field data in both a large observation area and in a smaller close-up view to the vortex core. Additionally, rotor blade deformation, airloads, and noise radiation were measured to form a complete, consistent, and comprehensive data base. Another 'first time' was the application of the blade position measurement technique SPR (Stereo Pattern Recognition), which provided instantaneous optical measurement of the blade bending in flap, lead-lag and torsion. In this paper, the HART II test is described in detail, including a description of all measurement techniques applied and with some results from each of them.

van Dinther, D., Hartogensis, O. K. and Holtslag, A. A. M.

"RUNWAY WAKE VORTEX, CROSSWIND, AND VISIBILITY DETECTION WITH A SCINTILLOMETER AT SCHIPHOL AIRPORT"

Boundary-Layer Meteorology, Vol. 157, 2015, pp. 481-499.

We evaluate the performance and investigate the capability of a scintillometer to detect wake vortices, crosswind, and visibility near an airport runway. An experiment is carried out at Schiphol airport (Amsterdam, The Netherlands), where an optical scintillometer is positioned alongside a runway. An algorithm is developed to detect wake vortices, and also the strength of the wake vortex, from the variance in the scintillation signal. The algorithm shows promising results in detecting wake vortices and their strengths during the night. During the day, the scintillometer signal is dominated by environmental turbulence and wake vortices are no longer detectable. The crosswind measured by the scintillometer is compared with wind-speed and wind-direction data at the airport. Our results show that, after applying an outlier filter, the scintillometer can measure the crosswind over the short time period of 3s required for aviation applications. The outlier filter does not compromise the capability of the scintillometer to obtain the maximum 3s crosswind over a 10-min time frame correctly. Finally, a transmission method is used to obtain the visibility from the scintillometer signal, which is then compared with that obtained from a visibility sensor. The scintillometer can identify periods of low visibility correctly, although it shows a high amount of scatter around the exact visibility value.

van Doorn, E., Dhruva, B. and Sreenivasan, K. R.

"STATISTICS OF WIND DIRECTION AND ITS INCREMENTS"

Physics of Fluids, Vol. 12, No. 6, June 2000, pp. 1529-1534.

We study some elementary statistics of wind direction fluctuations in the atmosphere for a wide range of time scales (0.0001 sec to 1 hr), and in both vertical and horizontal planes. In the plane parallel to the ground surface, the direction time series consists of two parts: a constant drift due to large weather systems moving with the mean wind speed, and fluctuations about this drift. The statistics of the direction fluctuations show a rough similarity to Brownian motion but depend, in detail, on the wind speed. This dependence manifests itself quite clearly in the statistics of wind-direction increments over various intervals of time. These increments are intermittent during periods of low wind speeds but Gaussian-like during periods of high wind speeds.

van Es, G. W. H.

"A REVIEW OF CIVIL AVIATION ACCIDENTS, AIR TRAFFIC MANAGEMENT RELATED ACCIDENTS: 1980-1999"

4th International Air Traffic Management R&D Seminar, December 2001, Santa Fe, NM.

The National Aerospace Laboratory NLR was contracted by the Air Traffic Control the Netherlands (LVNL) to collect and analyze a selected several air traffic management (ATM) related accidents. The objective of the present study was to quantify the historical safety performance in terms of accident

rates of a selected number of ATM related accident types. This information can assist in the determination of target levels of safety. This paper presents an analysis of ATM related accidents involving commercial civil transport aircraft which occurred worldwide during the period 1980-1999. ATM related accident rates by event type, flight phase and world region are presented and discussed.

van Es, G. W. H. and Karwal, A. K.

"SAFETY ASPECTS OF TAILWIND OPERATIONS"

NLR TR-2001-003, January 2001, National Aerospace Lab., Amsterdam, The Netherlands

In the present study the safety aspects of aircraft takeoff and landing operations in tailwinds are explored. The study covers a description of legislative instruments that influence preferential runway selection in relation to the maximum tailwind component applied; tailwind certification issues; and relevant safety issues concerning tailwind operations in general. Also, a systematic analysis of historical tailwind related overrun accidents and incidents is presented.

van Es, G. W. H. and van der Geest, P. J.

"A STUDY OF NORMAL OPERATIONAL LANDING PERFORMANCE ON SUBSONIC CIVIL NARROW BODY JET AIRCRAFT DURING ILS APPROACHES"

NLR-CR-2006-048, December 2006, National Aerospace Laboratory, Amsterdam, The Netherlands.

The need for improved capacity at airports to accommodate the rapid growth of domestic air traffic in the United States has led to the investigation of Landing and Hold Short Operations (LAHSO) as a safe and feasible means to increase the traffic flow. While the capacity issue becomes important, it is imperative that the increase in capacity does not lead to a safety decline. A key task is to investigate the aircraft landing performance as to provide operations safety guidelines for reducing the risks of incidents and accidents associated with LAHSO. For this a clear knowledge of the day-to-day landing operation is required. The present study is conducted using in-flight recorded data collected from day-to-day landing operations. These data were obtained from the quick access recorder for two types of narrow body aircraft, the B737-400 and the A319/A320/A321. Data from quick access recorders can be used to analyze aircraft performance. Aircraft landing field performance is influenced by many variables. Some variables have a more dominating influence than others. Some variables that have a strong influence are height above the threshold, speed loss from flare initiation to touchdown, and the available runway length for landing. However, there is not one single factor that really dominates the landing field performance.

van Garrel, A., ten Pas, S., Venner, C. H. and van Muijden, J.

"WIND TURBINE AERODYNAMICS FROM AN AEROSPACE PERSPECTIVE"

AIAA Paper 2018-0991, January 2018, Kissimmee, FL.

The current challenges in wind turbine aerodynamics simulations share a number of similarities with the challenges that the aerospace industry has faced in the past. Some of the current challenges in the aerospace aerodynamics community are also relevant for today's wind turbine aerodynamics community and vice versa. This paper sketches these similarities in broad strokes and points out the possibilities to revive solutions from the aerospace aerodynamics community from the 1960's onward that, with some modifications, can be applied to wind turbine aerodynamics problems. Opportunities are indicated where both the wind turbine and the aerospace aerodynamics communities can benefit from collaborative research.

van Gastel, P. A. and van Staveren, W. H. J. J.

"AIRCRAFT RESPONSES TO ATMOSPHERIC TURBULENCE. A COMPARATIVE STUDY"

Report LR-778, December 1994, Technical University of Delft, Delft, The Netherlands.

A comparison is made between the methods as presented in references (Etkin, 1972), (Etkin, 1980), (Robinson, 1991) and (Mulder & van der Vaart, 1993). Both the Delft University of Technology (DUT) and Etkin's Four Point Aircraft (FPA) models presented herein simplify the characteristics of atmospheric turbulence greatly. The differences between the two methods appear to be small in output power spectral densities results. The aircraft models, for both the DUT and FPA theory, are equal for most turbulence inputs. However, the approach in calculating the input power spectral densities differs considerably. The results, described by output power spectral densities, coincide over a wide frequency range.

van Holten, T., Jacken, A., Schoones, M. M. J. and Heiligers, M. M.

"THROTTLING A LAVAL NOZZLE BY A VORTEX: AN ANALYTICAL THEORY"

AIAA Paper No. 2007-1282, Reno, NV, January 2007

This paper presents an analytical theory for a vortex flow through a Laval nozzle. It will demonstrate that when a vortex is present the total velocity reaches sonic conditions upstream of the nozzle throat, that the axial velocity in the nozzle throat is equal to the local speed of sound and that the mass flow through the Laval nozzle depends on the vortex strength in such a way that the mass flow decreases with increasing vortex strength. The predictions of the analytical theory have been compared to the results of experiments and a numerical simulation, and it can be concluded that the analytical theory describes the characteristics of the flow very well.

Van Hoydonck, W. R. M., Haverdings, H. and Pavel, M. D.

"A REVIEW OF ROTORCRAFT WAKE MODELING METHODS FOR FLIGHT DYNAMICS APPLICATIONS"

35th European Rotorcraft Forum, Paper 101221, September 2009, Hamburg, Germany.

In this paper, the results of a brief survey in the field of rotorcraft inflow and wake modeling developments are presented. For many years, inflow models have been augmented with (semi-) empirical and analytical models to remove restrictions present in dynamic inflow models. In the meantime, significant algorithmic advances have been made in the field of Lagrangian free wake methods. This review summarizes the state of the art in rotor wake and inflow modeling for flight dynamics applications, and outlines benefits and limitations of both methods. As a result of this survey, our future research will focus on the development of a simplified free wake model where all vorticity is located on a continuous, truncated cylinder that can deform freely under its own influence.

van Jaarsfeld, J. P. J., Holten, A. P. C., Elsenaar, A., Trieling, R. R. and van Heijst, G. J. F.

"WIND TUNNEL EXPERIMENTS ON WAKE VORTEX DECAY IN EXTERNAL TURBULENCE"

AST4-CT-2005-012238, May 2007, Technical University Eindhoven, Eindhoven, The Netherlands.

In this study we present an experimental investigation of the evolution of both single and double wing-tip vortices in a wind tunnel with and without a turbulence generating grid, where $R = 40,000$ typically. Cross sectional velocity fields were obtained by means of particle image velocimetry at several locations downstream of the airfoil. Special attention was given to resolve the vortex core, since this has often been a region of difficulty in most experimental investigations. The single vortex was found to exist of a small viscous core and an outer region with nonzero vorticity. The decay of the maximum azimuthal velocity is close to laminar, both with and without grid. The main effect of the grid turbulence is to increase the diffusion of vorticity in the outer region and to enhance the wandering of the vortex center. The wandering amplitude is inversely proportional to the strength of the vortex, indicating mutual interaction between the vortex and external turbulence. For the double wing tip vortices, a split wing configuration was used with three different tip spacings. The vorticity distribution of the double vortices is more compact than that of the single vortex but decays due to cross-diffusion. The cross-diffusion is without grid significantly larger than viscous diffusion and enhanced by grid turbulence. Grid turbulence is also found to promote the onset of the Crow instability. The instability causes the vortex centers to oscillate with an angle of approximately 33 degrees to the horizontal. The growth rate of the oscillation amplitude is approximately half the growth rate predicted by inviscid theory. The Crow instability is followed by the phenomenon of vortex linking, which results in a rapid destruction of the vortices. At very strong turbulence levels, core oscillations and decay of circulation are significantly present, though the Crow instability is no longer observed.

van Jaarsveld, J. P. J., Holten, A. P. C., Elsenaar, A., Trieling, R. R. and van Heijst, G. J. F.

"AN EXPERIMENTAL STUDY OF THE EFFECT OF EXTERNAL TURBULENCE ON THE DECAY OF A SINGLE VORTEX AND A VORTEX PAIR"

Journal of Fluid Mechanics, Vol. 670, 2011, pp. 214-239.

This study is concerned with the effect of external turbulence on the decay of vortices. Single vortices and vortex pairs were generated with wing(s) mounted in the sidewalls of a wind tunnel. The distance

between the two vortices could be adjusted such that they just touched each other or overlapped. The intensity of the turbulence could be controlled with a turbulence grid. The development of the vortex was measured at several downstream stations with particle image velocimetry for a range of wing settings. The results indicate that the single vortex can be described by the 'two length scales' model of Jacquin, Fabre and Geffroy. A vortex core, which decays like a Lamb-Oseen vortex, is embedded in a region with an almost constant radius and a much lower azimuthal velocity that obeys a r to the minus beta power law, with r being the radius measured from the vortex center. For the turbulence levels and the test section length used in this study, the single-vortex behavior is independent of the external turbulence and in contrast with the decay of the vortex pair that strongly depends on the external turbulence. In the initial stages of the vortex pair evolution, the vortices decay due to cancellation of vorticity at the symmetry plane. At a later stage, Crow oscillations are observed, followed by a breakdown of the vortices. This vortex breakdown might be due to direct turbulent action. The observed behavior is in agreement with the theoretical model of Crow and Bate..

van Jaarsveld, J. P. J., Holten, A. P. C., Elsenaar, A., Trieling, R. R. and van Heijst, G. J. F.

"WIND TUNNEL EXPERIMENTS ON WAKE-VORTEX DECAY IN EXTERNAL TURBULENCE"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

It is well known from numerical studies that external turbulence promotes the decay of wake vortices, either by increased vorticity diffusion or by triggering 3D instabilities that lead to their destruction. So far, however, very few quantitative laboratory studies have been devoted to the issue of wake-vortex decay. In this study, we present an experimental investigation of the evolution of both single and double wing-tip vortices in a wind tunnel with and without a turbulence generating grid, where the Reynolds number is typically 40000. Particle image velocimetry measurements of the cross-sectional velocity field at several locations downstream of the airfoil show that for a single vortex the decay of the maximum azimuthal velocity is close to laminar, both with and without grid. The main effect of the grid turbulence is to enhance the wandering of the vortex center. Special attention was given to resolve the vortex core, since this has often been a region of difficulty in most experimental investigations. For the double wing-tip vortices a split wing configuration was used with three different tip spacings. External turbulence is found to promote the onset of the Crow instability and to enhance cross diffusion of vorticity. The Crow instability is followed by the phenomenon of vortex linking, which results in a rapid destruction of the vortices. At very strong turbulence levels, core oscillations and decay of circulation are significantly present, though Crow instability is no longer observed.

van Jindelt, T., van der Burg, J. W., vander Weide, E. T. A. and Hoeijmakers, H. W. M.

"NUMERICAL INVESTIGATION OF VORTEX BREAKDOWN"

AIAA Paper 2016-4174, June 2016, Washington, DC.

The computational prediction of maximum lift for a high-lift configuration of transport aircraft still poses a challenge. The accurate computational prediction depends on the ability to accurately represent the physical flow features involved in high-lift flow. For a transport aircraft with wing mounted engines the breakdown of vortices from the nacelle strakes can be a dominant flow feature determining maximum lift. In this paper a study is presented that focusses on investigating vortex breakdown numerically. Effort has been spent to find an experiment in which vortex breakdown can be investigated independently of major interaction of surrounding physical flow features as is the case in the flow over high-lift configurations. Aim of the study is to identify practices in current available Computational Fluid Dynamics (CFD) capabilities that are necessary to accurately represent vortex breakdown and understand why. Furthermore, it is assessed whether further validation data is required. In particular, the focus is on the level of physical modelling (turbulence model) and the computational strategy (executing steady or unsteady flow computations) needed to adequately predict vortex breakdown. One of the main conclusions of the study is that basic physical features of vortex breakdown can be captured in a turbulent flow computation, provided that in the numerical method the Reynolds stresses are considered.

van Kuik, G. A. M., Sorensen, J. N. and Okulov, V. L.

"ROTOR THEORIES BY PROFESSOR JOUKOWSKY: MOMENTUM THEORIES"

Progress in Aerospace Sciences, Vol. 73, 2015, pp. 1-18.

This paper is the first of two papers on the history of rotor aerodynamics with special emphasis on the role of Joukowski. The present one focuses on the development of the momentum theory while the second one surveys the development of vortex theory for rotors. Joukowski has played a major role in these developments. Although he cooperated with other famous aerodynamicists like Prandtl, his contribution is not well recognized as most of his publications are in Russian. The paper discusses the role of the English, Russian and German research schools of the Twentieth Century, and the contributions by individual researchers like Lanchester, Prandtl, Betz and Joukowski himself. After the one-dimensional momentum theory was well established, the introduction of torque and angular momentum was the next step. Joukowski has led the basis for this next step, but Glauert's Blade Element Momentum still is the basis of current rotor design codes. He applied some assumptions limiting the validity to moderate and high tip speed ratios. Sorensen and van Kuik published a solution for wind turbines with very low tip speed ratios, which is now expanded to propellers as well, with one remaining assumption of inviscid flow. For very low tip speed ratios the general momentum theory gives unphysical results which disappear after applying a perturbation parameter representing phenomena not captured by the Euler equations.

van Staveren, W. H. J. J.

"ANALYSES OF AIRCRAFT RESPONSES TO ATMOSPHERIC TURBULENCE"

PhD Thesis, Dec. 2003, Delft University of Technology, Delft, The Netherlands.

The response of aircraft to stochastic atmospheric turbulence are studied in the framework of three mathematical models, (1) the classical Delft University of Technology (DUT) model and (2) the classical Four Point Aircraft (FPA) model, and (3) a newly developed Parametric Computational Aerodynamic (PCA) model. From the results presented, it is concluded that the introduced PCA-model is the most accurate for all considered gust fields. Compared to the Linearized Potential Flow solution (which is assumed to be the benchmark, or the model that approximates reality closest) the new parametric model shows increased accuracy over the classical parametric models (the DUT- and FPA-model), especially for the aircraft responses to 2D gust fields. Furthermore, it shows more accuracy in the aircraft responses to 1D longitudinal gust fields. Although results will be presented for a Cessna Ce550 Citation II aircraft only, the theory and methods are applicable to a wide variety of fixed-wing aircraft, that is from the smallest UAV to the largest aircraft (such as the Boeing B747 and the Airbus A380).

Van Woortman, H. J. B. and Polak, F. R.

"A VORTEX ADVISORY SYSTEM AT SCHIPHOL/AMSTERDAM AIRPORT: FEASIBLE AND MEANINGFUL?"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 5-1 - 5-15

The results are given of an aircraft wake vortex measurement program. A wind criterion for a future Vortex Advisory System has been established. Actual wind data for Schiphol Airport, the Netherlands, concerning 11 months in 1980/81 have been analyzed with respect to the feasibility of a VAS-ellipse criterion (semi-axes 7 x 13 kts). The results are based on the peak hours for inbound traffic for runway 06. On average the wind vector lies within the ellipse criterion during more than half the total time a runway can be used. In case the wind vector lies within the ellipse, it takes generally not long in succession: in 70% it takes less than 4 minutes. Although a low number of ellipse transitions per hour prevails, transitions of higher frequency (> 5 per hour) do occur often enough (30% of total time) to cause problems for the controller to determine whether separations must be changed or not. The effect of the above-mentioned frequent ellipse transitions can be reduced using a buffer zone. By using a 3kts buffer zone around the ellipse criterion and keeping the 'red light' on if this zone is not exceeded, about 60% of the highly frequent transitions will be eliminated. These are the transitions which exceed the ellipse boundary with less than 3 kts. The 'attention time' are generally very short (< 5 min. in 90% of the cases). The 'warning times' are even shorter. It is a general feeling that the present results indicate that the operational benefit of a VAS for Schiphol Airport will be very limited. The main reason for this opinion is that, although the ellipse criterion as such is reliable, due to the rapid and almost unpredictable wind variations which do often occur at Schiphol, the operationally acceptable buffer zone or time lag will probably be so large that, effectively the controller will have to apply large separations almost all the time.

van Zyl, I.

"EXTREMUM-SEEKING CONTROL FOR CONSTRAINED OPTIMAL FORMATION FLIGHT OF COMMERCIAL AIRLINERS"

MS Thesis, March 2018, Stellenbosch University, Matieland, South Africa.

Formation flight of commercial airliners has become a topic of interest due to the possibility of significant fuel savings. With air traffic rapidly increasing, the aeronautical industry recognizes the necessity to improve fuel efficiency of long-distance flights. Previous studies have shown that extended formation flight of existing commercial aircraft is plausible, but have not dedicated much attention to fully utilizing the wingtip generated wakes. This study presents the design, implementation, and verification of a perturbation-based extremum-seeking controller that enables follower aircraft to locate and maintain optimal formation separations in a practical formation flight scenario. Typically, the trailing vortices of the leader aircraft are displaced due to atmospheric disturbances, such as static winds and turbulence, and models of the vortex positions are not exact. Due to the dangers related to flight deep in the leader's wake, a novel constrained objective function is proposed that prevents the extremum-seeking controller from guiding the follower aircraft too close to the vortex core. In this constrained objective function, the extremum is represented by a constrained extremum contour instead of a single point. A novel extremum-seeking state machine is proposed that controls the different modes of operation that the follower aircraft transitions through as it approaches the constrained extremum. The states and the state transition boundaries are defined as functions of the objective function, which allow them to follow the displaced trailing vortex, instead of remaining static relative to the leader aircraft. This also enables the extremum-seeking control to not only track a static trailing vortex, but also a constrained extremum for a dynamic trailing vortex. It is also shown that by approaching the constrained extremum at a constant approach rate, rather than the classical proportional approach rate, the effects of the non-linear wake on the seeking performance may be mitigated. The extremum-seeking controller was verified in simulation on a formation flight model of two Boeing 747 aircraft in right echelon formation. The formation is subjected to realistic atmospheric disturbances and sensor noise. The simulation results show that the extremum-seeking controller is able to successfully guide the follower to the constrained extremum, even in the presence of varying static wind and light turbulence, and that thrust reduction of up to 23 percent may be achieved.

Vancassel, X.

"SIMULATION OF AEROSOLS IN NEAR-FIELD AIRCRAFT PLUMES: APPLICATION TO MESO-SCALE MODELS INITIALISATION"

9th ONERA-DLR Aerospace Symposium, October 2008, Chatillon, France.

One of the challenges in assessing the aviation impact on the atmosphere lies in the correct consideration of the various processes involved. These have to be captured for very different time and spatial scales, from molecular to the earth's size. The global impact of aviation on the atmosphere is generally determined using the total amount of gas and particulate matter emitted by aircraft, as a function of the flight routes used. But the results of their interaction with the background species obtained from CTM (Chemistry Transport Model) generally ignore some of the physical and chemical transformations occurring at much smaller scales in the aircraft plume. Microphysical and chemistry models have been developed to take the plume chemistry and microphysics into account. They are most of the time trajectory box models which are run along an average plume. They can also be coupled online with aerodynamics models but in that case, they must be simplified to minimize

computation costs. In the paper, we present an offline alternative method based on the use of an ensemble of OD boxes and a detailed plume aerosol model. The results show the different particles properties, especially volatile but also ice (size distribution, composition, etc.) and emphasize the influence of mixing.

Vancassel, X., Mirabel, P. and Francois, G.

"NUMERICAL SIMULATION OF AEROSOLS IN AN AIRCRAFT WAKE USING A 3d LES SOLVER AND A DETAILED MICROPHYSICAL MODEL"

International Journal of Sustainable Aviation, Vol. 1, No. 2, 2014, pp. 139-159.

The global impact of aviation on the atmosphere is generally determined using the total amount of gas and particulate matter emitted at the aircraft engine exit but generally ignore some of the physical transformations occurring at much smaller scales in the aircraft wake. In this work, we present an offline alternative method based on the use of a detailed plume aerosol model combined to fluid trajectories calculated from 3D large-eddy simulations (LESs). The study has been limited to the first 10 s behind a type Airbus 340 aircraft. The results have been compared to those obtained from a one-way coupling approach including a simple microphysics water vapor deposition model on soot cores. The respective evolutions of average ice particles radius are in good agreement. Furthermore, different types of aerosol properties are examined including the charged volatile particles, the dry and activated soot, and the ice crystals from homogeneous and heterogeneous freezing. The variability of the aerosol size distribution clearly illustrates the influence of the mixing, as a function of the position in the aircraft plume. Finally, the volatile particles distribution exhibits a bimodal shape resulting from the presence of charges, in agreement with that observed experimentally.

vanDam, C. P.

"INDUCED-DRAG CHARACTERISTICS OF CRESCENT-MOON-SHAPED WINGS"

Journal of Aircraft, Vol. 24, No. 2, February 1987, pp. 115-119.

Results are presented of a theoretical study conducted to analyze the potential drag reduction characteristics of wings with highly tapered aft-swept tips at subsonic speeds. These planar wings, also named crescent-moon-shaped wings or wings with curved planform, can produce induced drag less than the minimal value obtained with the classical unswept elliptical wing for a constant lift and wing span. The induced-drag reduction is the result of the nonplanar wing and wake shape at the angle of attack. For an example wing of aspect ratio 7, the crescent-moon shape provides a reduction in cruise induced drag of 8.0 percent as compared to an unswept elliptical wing.

Vandernoot, F.-X., Barricau, P., Bezard, H. and Boisson, H.-C.

"MEAN AND TURBULENCE MEASUREMENTS OF WAKE VORTICES. WANDERING EFFECTS."

14th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 2008.

Experiments have been performed in a hydrodynamic tunnel behind a generic half-wing equipped with an inboard flap, up to 9 wingspans downstream using two-component Laser Doppler Velocimetry and three-component Particle Image Velocimetry. A half wing model of constant chord, full aspect ratio equal to 4, rounded wingtip and NACA0012 wing section has been used. The inboard flap which allows to get two co-rotating vortices extends over 80 percent of the half-span and 30 percent of the chord. The deflection angle can be set to 0 degrees (clean case), 4, 6 or 8 degrees. The upstream velocity is equal to 4 m/s which corresponds to a Reynolds number based on chord of about 300,000. The LDV campaign has provided a characterization of the near wake in cross planes at 0.1 and 0.25 wingspans downstream the trailing edge. Besides, the spanwise load distribution has been estimated by measurements along closed path around the wing sections. The PIV campaign, during which the setting of the coplanarity of the laser sheet and the calibration plate was revealed of first importance, has supplied the complete velocity and turbulence fields in cross planes scattered in the extended near wake between 1.27 and 8.74 wingspans downstream the wing. Furthermore, the wandering phenomenon, i.e. the slow side-to-side vortex motion which strongly alters the measurements, has been considered carefully. A procedure was implemented to delete the over diffusion and the overwhelming excess of turbulence artificially induced by this phenomenon in the vortex core.

Vandernoot, F.-X., Bezard, H., Barricau, P. and Boisson, H.-C.

"MEAN AND TURBULENCE MEASUREMENTS OF WAKE VORTICES, WANDERING EFFECTS"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 200.

The aim of the present study is to accurately characterize the rollup behind a generic wing equipped with an inboard flap deflected at different angles. The wandering effects are clearly identified and corrected. A half wing model of 75 mm chord, 150 mm half-span (aspect ratio equal to 4), rounded wingtip and NACA0012 wing section was used. The flap extends over 80 percent of the half-span and 30 percent of the chord. The flap angle can be set to 0 degrees (clean case), 4, 6 or 8 degrees. The experiments were carried out in the hydrodynamic tunnel THALES of the ONERA/DMAE (upstream velocity, 4 m/s; Reynolds number based on chord, around 300,000). To quantify the aerodynamics of the wing, a LDV system was used to measure the velocity along closed paths around the wing profile in different sections to estimate the spanwise load distribution and to connect it to the circulation of the wake vortices thanks to Betz's theory. To quantify the rollup for the different configurations of the wing, a stereoscopic PIV system was used to measure cross planes until almost 9 wingspans downstream. The angles of attack were chosen so that comparisons between the flap angles could be made at the same angle of attack or at the same lift. The mean fields of the three velocity components, the axial vorticity, and the six Reynolds stresses were measured with success. Classical phenomena, such as the diffusion of a single vortex or the behavior of a two-vortex system, were clearly identified from one cross plane to another.

Vanhoenacker-Janvier, D., Djafri, K., della Faille de Leverghem, R., van Swieten, B. and Barbaresco, F.

"SIMULATION OF THE RADAR CROSS-SECTION OF WAKE VORTICES IN CLEAR AIR"

ERAD 2012, 7th Conf. on Radar in Meteorology and Hydrology, June 2012, Toulouse, France.

Real-time sensing of Wake Vortices at take-off and landing is a key issue for the implementation of new air traffic management systems for reduced aircraft separation in favorable weather conditions and for increased air safety. In the framework of SESAR P12.2.2 project, a model has been developed at UCL for the calculation of the radar cross-section of the wake vortices, in a wide frequency range. The first step is the simulation of the evolution of pressure, temperature, and humidity versus time, during the landing phase of the aircraft. These parameters are calculated using a pseudo-spectral code developed at UCL and then used for the calculation of the refractive index of the atmosphere under stratified conditions. They are represented in a plane perpendicular to the airplane velocity and evolving with time. The next step is the calculation of the radar cross-section of the various elements of the 3D-grid. The integrand is composed of a rapidly oscillating function in the frequency range of interest. The method of Li has been implemented for the resolution of the integral. The integration method necessitates interpolation between the elements of the grid. Simulations can be calculated for various airplanes weight and span, various speeds, various stratifications of the atmosphere, represented by Brunt-Vaisala constant.

Vanhoenacker-Janvier, D., Djafri, K. and Barbaresco, F.

"MODEL FOR THE CALCULATION OF THE RADAR CROSS SECTION OF WAKE VORTICES OF TAKE-OFF AND LANDING AIRPLANES"

ERAD 2012, 7th Conf. on Radar in Meteorology and Hydrology, June 2012, Toulouse, France.

A new model has been developed for the calculation of the radar cross section and the power backscattered by wake vortices of take-off and landing airplanes to better understand the physical mechanisms involved, to compare with the measurements that will be performed in X-band by Thales during the SESAR P12.2.2 project and to prepare inputs for testing a Wake Vortex Advisory System. The model contains a first part that simulates the evolution of the vortex in stratified atmosphere, using simplified 2D fluid mechanics equations and uses the pressure, temperature and humidity for the calculation of the difference between the dielectric permittivity of the clear air and of the wake vortex. The second part calculates the power backscattered by the dielectric permittivity gradients in the vortex. The input parameters describe the atmosphere as well as the airplane of interest. Simulation results have been compared with results published in the literature, when all the input parameters are available.

Vanierschot, M.

"ON THE DYNAMICS OF THE TRANSITION TO VORTEX BREAKDOWN IN AXISYMMETRIC INVISCID SWIRLING FLOWS"

European Journal of Mechanics B/Fluids, Vol. 65, 2017, pp. 65-69.

This paper reports on novel features found in the dynamics of the transition to vortex breakdown in inviscid axisymmetric flows with swirl. These features are revealed by a transient simulation of an open-ended pipe flow where the inlet swirl is suddenly increased from a swirl number just below the onset of vortex breakdown to a swirl number just above the onset of vortex breakdown. To eliminate the numerous parameters influencing breakdown, the axisymmetric Euler equations with swirl are used as a fluid flow model and solutions are obtained by means of numerical simulation. It is shown that as the step response has died out, the flow evolves to a quasi-static state where time derivatives of variables are negligible small. Stability analysis of this state shows that it can support standing waves in a small region of the flow domain. These standing waves are observed in the simulations as an imbalance in the axial momentum equation which slows down the flow near the central axis. The amplitude of this imbalance grows exponentially in time with a dimensionless growth rate of 0.83 scaled with the flowthrough time. Eventually, the axial velocity along the central axis becomes negative in a small part of the flow, leading to an axisymmetric recirculation zone, called vortex breakdown. To the authors knowledge, this study would be the first to reveal these features prior to breakdown and the results may help in understanding of the physical mechanisms leading to it as this is still a controversial issue in literature.

Vanneste, J. and Young, W. R.

"ON THE ENERGY OF ELLIPTICAL VORTICES"

Physics of Fluids, Vol. 22, 2010, pp. 081701-1 - 081701-4.

Consider a two-dimensional axisymmetric vortex with circulation G . Suppose that this vortex is isovortically deformed into an elliptical vortex. We show that the reduction in energy is $-(G^2) \ln[(q + 1/q)/2]/(4\pi)$, where q^2 is the ratio of the major to the minor axis of any elliptical vorticity contour. It is notable that the reduction in energy is independent of the details of vorticity profile of the axisymmetric vortex and independent of its average radius. The implications of this result for the two-dimensional inverse cascade are briefly discussed.

vanZyl, L. H.

"UNSTEADY PANEL METHOD FOR COMPLEX CONFIGURATIONS INCLUDING WAKE MODELING"

Journal of Aircraft, Vol. 45, No. 1, January-February 2008, pp. 276-285

The calculation of unsteady air loads is an essential step in any aeroelastic analysis. The subsonic doublet lattice method is used extensively for this purpose because of its simplicity and reliability. The body models available with the popular implementations of the doublet lattice method are, however, not very versatile in terms of geometries that can be modeled. The ZONA6 code offers a versatile surface panel body model including a separated wake model, but uses a pressure panel method for lifting surfaces. This paper describes the development of an unsteady subsonic wing-body code based on the doublet lattice method, with a source panel representation of bodies, a separated wake flow

model based on the ZONA6 approach, and an approximate method of images to model wing-body interference. This approach provides greater flexibility in body shapes that can be modeled while retaining the reliability of the doublet lattice method for lifting surfaces.

Varriale, C., De Marco, A., Daniele, E., Schmidt, J. and Stoevesandt, B.

"FLIGHT LOAD ASSESSMENT FOR LIGHT AIRCRAFT LANDING TRAJECTORIES IN WINDY ATMOSPHERE AND NEAR WIND FARMS"

Aerospace, Vol. 5, No. 2, 2018, pp. 42-1 to 42-22.

This work focuses on the wake encounter problem occurring when a light, or very light, aircraft flies through or nearby a wind turbine wake. The dependency of the aircraft normal load factor on the distance from the turbine rotor in various flight and environmental conditions is quantified. For this research, a framework of software applications has been developed for generating and controlling a population of flight simulation scenarios in presence of assigned wind and turbulence fields. The JSBSim flight dynamics model makes use of several autopilot systems for simulating a realistic pilot behavior during navigation. The wind distribution, calculated with OpenFOAM, is a separate input for the dynamic model and is considered frozen during each flight simulation. The aircraft normal load factor during wake encounters is monitored at different distances from the rotor, aircraft speeds, rates of descent and crossing angles. Based on these figures, some preliminary guidelines and recommendations on safe encounter distances are provided for general aviation aircraft with considerations on pilot comfort and flight safety. These are needed, for instance, when an accident risk assessment study is required for flight in proximity of Aeolic parks. A link to the GitHub code repository is provided.

Varshney, K.

"UNSTEADY DYNAMICS OF WIND TURBINE WAKE, OSCILLATING BUBBLE AND FALLING CARD"

PhD Thesis, January 2009, University of Massachusetts, Amherst, MA.

Helical tip vortices in the wake of a wind turbine, dynamics of a rising and oscillating bubble and trajectories of cards falling under gravity have been investigated here. The near wake flow field of the wind turbine in the Reynolds number range 1000 to 5000 has been explored using qualitative dye flow visualization and quantitative digital particle image velocimetry (DPIV) techniques. Flow visualization studies showed the dye getting trapped in the shape of spirals surrounding the helical vortex cores. It was found that the helical vortex core size was increasing with downstream distance. It was also found that the normalized stream-wise component of the wake velocity decreased with increasing tip-speed ratios. The pitch of the tip vortex monotonically decreased with increasing tip-speed ratios. The evolution of the global wake vorticity field with time has been studied in detail, for the first time. The results indicated that vorticity peaks at the center of the core, as one would expect. The vorticity at the center of the core was also found to decay as the vortex moved downstream, implying that the viscous

dissipation was active even at length scales of few diameters. Power spectrum of the stream-wise velocity field at a point showed a distinctive peak at a frequency of 0.5 Hz.

Vasatka, J. E.

"THE DYNAMIC RESPONSE OF A TWIN-ENGINE, COMMERCIAL JET TRANSPORT TO WAKE VORTEX ENCOUNTERS"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 14-1 to 14-1.

To refine existing wake-vortex separation distances through the application of technology, the issues associated with defining the basis for separation criteria must be addressed. This includes understanding the significance of a wake vortex encounter. To further the process of understanding the significance of such encounters, a flight simulator was used to evaluate the response of a jet-transport aircraft to wake-vortex encounters. The objective was to evaluate the response of a twin-engine, commercial jet transport to a variety of wake characteristics and operational assumptions. The study was conducted using a modified simulation of a twin-engine, commercial jet transport. The simulations included: (1) the free response of a trimmed airplane encountering a wake; (2) the response of an airplane controlled by only the autopilot; and (3) the response of an airplane controlled by a 'math pilot' designed to maintain wings level. The latter two modes of airplane control were chosen in order that the airplane response could be evaluated without incurring the variation associated with pilot-in-the-loop simulations. The results from this study suggest that the airplane's response is dependent on the flight path through the wake.

Vasatka, J. E.

"AN OVERVIEW OF WAKE VORTEX ISSUES AND THE ACTIVITIES OF THE GOVERNMENT/INDUSTRY TEAM"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Quebec, Canada, December 1997, pp. 41-42

The continuing growth of air travel and the increasing application of technology for managing air traffic is changing the environment of the air traffic system. Maintaining or enhancing the existing level of safety while improving productivity in this changing environment will require careful consideration to the underlying assumptions incorporated into the existing system. Research efforts presently under way around the world are addressing many aspects of the wake turbulence issue. However, no single organization has the breadth of expertise or the resources required to address the issues associated with developing and implementing solutions for wake-turbulence related issues. Therefore, to enhance safety and mitigate unnecessary capacity limitations placed on the system, the Government/Industry Team is identifying how to combine the efforts of many organizations to ensure that a focused, coordinated wake-turbulence plan is implemented and that it has constancy of purpose, clear and obtainable goals, strong leadership, and adequate resources.

Vasile, J. D.

"EFFECT OF A PITCH-OSCILLATING CANARD ON LIFT ENHANCEMENT AND TIP VORTEX MITIGATION"

AIAA Paper 2017-0717, January 2017, Grapevine, TX.

A two-dimensional NACA 0012 airfoil and three-dimensional NACA 0015 canard undergoing a dynamic ramp pitch-oscillating motion was investigated computationally. The effect of amplitude and reduced frequency on augmenting lift for both configurations was considered. The study showed lift enhancement for both configurations at freestream Mach number = 0.5 and = 0.2 for all amplitudes and reduced frequencies at angles of attack post stall. Furthermore, the effect of the dynamic motion on the development of the tip vortex was explored. The time-averaged flow solution for the pitch-oscillating canard revealed lower vorticity magnitude and less coherence of the tip vortex downstream. For the parameters investigated, increasing the amplitude of the oscillation proved to be the most effective in enhancing lift as well as reducing the strength of the tip vortex. The encouraging results indicate that further research in unsteady aerodynamics to increase the control authority of canard-controlled projectiles is necessary.

Vasilescu, R.

"HELICOPTER BLADE TIP VORTEX MODIFICATIONS IN HOVER USING PIEZOELECTRICALLY MODULATED BLOWING"

PhD Thesis, November 2004, Georgia Institute of Technology, Atlanta, GA.

In this thesis, piezoelectrically modulated and/or vectored blowing at the rotor blade tip is theoretically investigated as an active technique for modifying the structure of the tip vortex core as well as for increasing blade vortex miss distance. The mechanisms of formation and convection of rotor blade tip vortices up to and beyond 360 degrees wake age are described based on the CFD results for the baseline cases of a hovering rotor with rounded and square tips. A methodology combining electromechanical and CFD modeling is developed and applied to the study of a piezoelectrically modulated and vectored blowing two-dimensional wing section. The thesis is focused on the CFD analysis of rotor flow with modulated tangential blowing over a rounded blade tip, and with steady mid-plane blade tip blowing, respectively. Computational results obtained for steady tangential blowing indicate that the miss distance can be doubled compared to the baseline case, which may lead to a significant reduction in BVI noise level if this trend shown in hover can be replicated in low-speed forward flight. Results also show that through modulated blowing a higher dissipation of vorticity can be obtained.

Vasilescu, R. and Dancila, D. S.

"ROTOR WAKE MODIFICATIONS IN HOVER USING UNSTEADY SPANWISE BLOWING"

AIAA Paper No. 2006-1065, Reno, NV, January 2006

2200

A Computational Fluid Dynamics (CFD) study investigating the effects of unsteady spanwise rotor blade tip blowing on the formation and evolution mechanisms of blade tip vortices shed during hover is presented in this paper. The specific blowing configuration consists of a single jet sheet with modulated mass flow rate controlled through slot area variation, ejected tangentially over a rounded blade tip cap. By using the beneficial Coanda effect of jet attachment to the curved wall of the blade tip cap a downward deflection of the jet sheet direction is obtained. As a consequence the location and formation of the tip vortices are modified in a time dependent manner with reference to a baseline, no-blowing case investigated for the same rotor and flight conditions.

Vasilescu, R., Ganesh, B., Dancila, D. S., Komerath, N. M. and Sankar, L. N.

"GEOMETRY TIP CAP EFFECTS ON FORMATION AND NEAR WAKE EVOLUTION OF THE ROTOR TIP VORTICES"

AIAA Paper No. 2006-3376, San Francisco, CA, June 2006.

A combined numerical and experimental investigation is performed on the fundamental aspects of tip vortex formation and convection mechanisms for a two bladed rotor. The paper is focused on identifying similarities and differences in the near wake fields caused by blade tip geometry modification. Two different configurations are investigated. The first one corresponds to a square blade tip while the second one corresponds to a rounded blade tip cap. PIV measurements of the crossflow velocities around the forming tip vortex were performed for a forward flight regime characterized by a 0.1 advance ratio. RANS simulations of the rotor flow were conducted for the same rotor configurations as used in the experimental tests but considering only the hover regime. Both experimental and numerical tests confirm that there is a qualitative difference in the tip vortex formation and evolution between the square blade tip and rounded blade tip configurations. This qualitative change is shown in the velocity distributions measured and computed around and downstream of the tip. It is explained by the differences in the flow separation identified for the two configurations.

Vatistas, G. H.

"NEW MODEL FOR INTENSE SELF-SIMILAR VORTICES"

Journal of Propulsion and Power, Vol. 14, No. 4, July-August 1998, pp. 462-469

A new model that can generate single- or double-celled steady, incompressible, intense vortices is proposed. As was evident in earlier experiments, depending on the values of scaling constants, it is shown that the axial-velocity component may attain profiles ranging from jet-like to wake-like. In general, the radial-velocity profile has a similar shape as the tangential velocity, developing a direction reversal near the axis of rotation when the two-celled vortex appears. For the case of a one-celled vortex, the tangential velocity behaves like that of Rankine's vortex with viscous smoothing near the core. However, as the reverse flow inside the core matures the tangential velocity reduces gradually from the forced-vortex profile while its maximum value is augmented. The evolution from a one-celled

to a two-celled vortex is also characterized by a migration of the vorticity peak from the central axis toward the core. The present theory suggests that the implementation of the experimental data for the tangential velocity near the core depends on the quality of the secondary flow.

Vatistas, G. H.

"SIMPLE MODEL FOR TURBULENT TIP VORTICES"

Journal of Aircraft, Vol. 43, No. 5, September-October 2006, pp. 1577-1579

Fifteen years ago, a family of laminar vortices was proposed by Vatistas et al. The most widely used member of the set is the $n=2$. Recently, the basic model was transformed to account for vortex decay. The formulation was further enlarged to include the effects of density variations. The present paper represents the first attempt toward capturing the overall effects of turbulence via a mathematically simple model. A probable reason for the historical preference to Scully's formulation in modeling tip vortices is also identified.

Vatistas, G. H. and Aboelkassem, Y.

"EXTENSION OF THE INCOMPRESSIBLE $n=2$ VORTEX INTO COMPRESSIBLE"

AIAA Journal, Vol. 44, No. 8, August 2006, pp. 1912-1915

The incompressible $n=2$ vortex model formulation has been extended to account for density variation via the use of energy equation and perfect gas law. The basic elements of the approach are anticipated to be applicable to examine phenomena such as vortex stability, compressible flow aeroacoustics, compressible vortex visualizations via shadowgraphs, and several others.

Vatistas, G. H. and Aboelkassem, Y.

"SPACE-TIME ANALOGY OF SELF-SIMILAR INTENSE VORTICES"

AIAA Journal, Vol. 44, No. 4, April 2006, pp. 912-917.

The theoretical development presented here provides a space-time duality for self-similar intense vortices. The methodology was first derived and then its validity was tested using several known classical vortices. In this Note, we have examined the similarity properties of a group of intense vortices. The system of equations that describes the general problem was condensed using a similarity variable that combines space and time. The revealed duality among the vortex decay and the steady-state subset made possible the transformation of various known vortex models from decaying to steady state and vice versa. Vortices of this type were found to remain concentrated and intense throughout the decay phase. In the presence of a meridional flow, the simplified problem is underdetermined, which explained the reason behind the emergence of a multitude of past solutions. The main characteristics of the analogy were justified by the data of various experimental studies.

Vatistas, G. H., Aboelkassem, Y. and Kamran Siddiqui, M. H.

"TIME DECAY OF n FAMILY OF VORTICES"

AIAA Journal, Vol. 43, No. 6, June 2005, pp. 1389-1391

The steady state vortex model of Vatistas, et. al, is further developed into a high Reynolds number time decaying model. Following the classical order-of-magnitude analysis and similarity transformation analogous to those in the development of boundary layer flow theory, a generalized transformation between a family of steady state vortices and their time varying counterparts are established. The well-known vortex profiles such as Lamb, Burgers and Survillan models can be seen as specialized cases of the generalized formulation described in this work.

Vatistas, G. H., Aboelkassem, Y. and Siddiqui, M. H. K.

"ON THE SPACE-TIME DUALITY OF INTENSE VORTICES"

AIAA Paper No. 2005-5159, Toronto, Canada, June 2005

In this paper, we present a general methodology whereby steady intense vortices are transformed into time decaying via an independent variable that combined space and time. The fundamental principle was then employed to extend the desingularized n - family of steady state vortices to become time dependent. Limited experimental data confirms the validity of the approach. The method is sufficiently general as to allow the conversion of any known vortex model of the same kind from steady to time decaying and visa versa.

Vatistas, G. H., Badwal, G. S. and Rampal, R.

"THERMAL PROPERTIES OF COMPRESSIBLE LINE VORTICES"

Journal of Aircraft, Vol. 54, No. 4, July-August 2017, pp. 1407-1414.

A simple mathematical model to simulate the temperature, pressure, and density distributions in intense turbulent compressible line vortices is reported. Based on the previous $n = 2$ member of the n family of vortices, a wider-range model that includes the rudimentary combined features of turbulence and compressibility is built. In antithesis to the previous laminar theoretical approaches, where the converging flow cooled down monotonically with decreasing radius, it is now discovered that, far from the axis of rotation, the gas is first heated up, reaching a static temperature maximum that is higher than the ambient value; then, it chills down to a subambient minimum at the vortex center. The cause of this effect is recognized to be the outcome of competition between two fundamental mechanisms: gas heating because of mechanical dissipation, and cooling due to mainly fluid parcel's dilation. Thus, the present investigation identifies the cause of the Ranque-Hilsch-like thermal effect observed in unconfined compressible vortices. In comparison to laminar vortices, the center of a turbulent gaseous

vortex is found to be cooler, thinner, and under lower-pressure conditions. All thermodynamic properties are shown to be functions of the vortex Mach number and level of turbulence.

Vatistas, G. H., Kozel, V. and Mih, W. C.

"A SIMPLER MODEL FOR CONCENTRATED VORTICES"

Experiments in Fluids, Vol. 11, 1991, pp. 73-76

A simple vortex model based on an empirical formula for the tangential velocity component was presented. A closed form solution for the static pressure which agrees well with the observed values was obtained. The model produced a radial velocity component which is bounded over the whole domain.

Vatistas, G. H., Lin, S. and Li, P. M.

"A SIMILAR PROFILE FOR THE TANGENTIAL VELOCITY IN VORTEX CHAMBERS"

Experiments in Fluids, Vol. 6, 1988, pp. 135-137

Forcing a fluid into a cylindrical chamber through either a series of tangential inlets, or a rotating porous circumferential wall will generate a strong confined vortex. In both cases a Rankine-like tangential velocity profile, with a viscous smoothening in the region where the vortex changes modes, will be produced. Recent experiments by Vatistas (1984) have shown the velocity to strongly depend on several flow parameters, and not to vary significantly along the height of the chamber. The latter observation is true for most of the vortex chamber flow except inside Ekman's boundary layers, at the top and bottom plates, where the tangential velocity is first expected to peak, and then reduce to zero. In the present note a similarity relationship for the radial profile of the tangential velocity is reported. Experimental data confirm the results of the analysis. Oseen's equation for an unconfined vortex is found to adequately approximate the confined vortex.

Vatistas, G. H., Panagiotakakos, G. D. and Manikis, F. I.

"EXTENSION OF THE n -VORTEX MODEL TO APPROXIMATE THE EFFECTS OF TURBULENCE"

Journal of Aircraft, Vol. 52, No. 5, September-October 2015, pp. 1721-1725.

The present work is an extension of the previous contribution of Vatistas on simple model for turbulent tip vortices. A generalized formula that encapsulates both the laminar and turbulent members of the n family of vortices that could also produce the turbulent equivalent of the Rankine and Kaufmann-Scully vortices was presented. The best correlation for the tangential velocity with the experimental tangential velocity data is shown to occur when n is equal to two. An approximate link of the turbulent parameter to the effective vortex Reynolds number was made. The present formulation was shown to perform better in approximating the wake of both laboratory and full-scale vortices than the traditional approaches.

Vaucher, G. T., Creegan, E. and Yarbrough, J.

"924-MHZ WIND PROFILING RADAR ACCEPTANCE TESTS"

ARL-TR-1815, November 1998, U.S. Army Research Laboratory, White Sands Missile Range, NM.

In March of 1998, the Artillery Branch of the Army Research Laboratory received a Reconstructed 924 MHz Wind Profiling Radar System. Over the subsequent months, several hardware tests were conducted to verify the successful functioning of the radar components and integrated system. In this technical publication, seven radar evaluation tests are documented. The first two radar evaluation tests, the Frequency Survey, and the Local Site and Internal Radar System Noise Tests, examine the non-operational environments for possible radar signal corruption sources. The radar signal itself is reviewed in the Radar Signal Analysis Test. Finally, the radar's components are isolated and evaluated in the 'I' and 'Q', Opposing Beams, System Noise Test: Pre-Amplifier, and System Noise Test: Distributed Amplifier Tests. Each Test explanation includes: (1) the Radar Test Purpose, (2) the Hardware/Test Setup and Materials, (3) the Test Description, and (4) the Results and Result Interpretation. Figures displaying specific hardware setup, or test results are included, as appropriate. Appended to the text are results from the initial radar verification exercise. Brief excerpts from the Radar Test logbook are included, to enhance the reader's understanding.

Vaughan, J. M.

"COHERENT LASER SPECTROSCOPY AND DOPPLER LIDAR SENSING IN THE ATMOSPHERE"

Physica Scripta, Vol. T78, 1998, pp. 73-81

The principles of coherent laser spectroscopy are briefly reviewed in which a signal beam is heterodyned with an optical local oscillator beam. The frequency and single mode selectivity this provides is shown to be very advantageous. This is illustrated by recent work on the properties of different classes of light held including the fractal character of Gaussian-Lorentzian light, and by several aspects of laser physics. In equivalent practical applications to remote sensing in the atmosphere, coherent Doppler lidar provides a powerful technique. This is illustrated by measurements of wind fields and aircraft wake vortices. Airborne equipment have been used for measurements of true airspeed, wind shear warning and atmospheric backscatter levels. Future space-borne lidars could potentially measure the global wind field – which would be of great benefit for numerical weather forecasting and climate studies.

Vaughan, J. M.

"WAKE VORTEX INVESTIGATIONS AT HEATHROW AIRPORT, LONDON"

Proceedings of 3rd Aero Days Post-Conference, Nouvelle Revue D'Aeronautique et D'Astronautique, No. 2, 1998, pp. 116-12.

Measurements of aircraft wake vortices by Laser Doppler Velocimetry (LDV) can provide unique, full-scale information on vortex generation, evolution, trajectory, and decay in the real atmosphere. During

trials at Heathrow nearly 3000 records of vortices from landing aircraft were made over 25 days between December 1994 and September 1995. Examples of some of the initial results are presented, including characteristic vortex signatures and profiles from different aircraft and analyses of vortex strength and trajectory. Because of their fine resolution, LDV measurements should enhance the understanding of the structure of vortices and the mechanisms, including meteorological conditions, governing their behavior. Vortex bursting for example is poorly understood but is likely to be the limiting factor in determining acceptable separation minima at airports. Application to airport operation is briefly discussed and the possible contribution to strategic and tactical decision making.

Vaughan, J. M. and Harris, M.

"LIDAR MEASUREMENT OF B747 WAKES: OBSERVATION OF A VORTEX WITHIN A VORTEX"

Aerospace Science and Tech., Vol. 5, August 2001, pp. 409-411.

Measurements of aircraft wake vortices obtained by laser radar techniques at London Heathrow Airport have revealed many interesting features of vortex structure. Notably, the vortices from Boeing 747 aircraft are shown to contain an intense, narrow-core vortex embedded within a larger co-rotating diffuse vortex. We propose an empirical 'double-dispersion' model consisting of the linear superposition of two concentric dispersion functions. This new model provides a good description of the B747 vortex, and should therefore be applicable in simulations of aircraft encounters with B747 vortices.

Vaughan, J. M., Brown, D. W., Constant, G., Eacock, J. R. and Foord, R.

"STRUCTURE, TRAJECTORY AND STRENGTH OF B747 AIRCRAFT WAKE VORTICES MEASURED BY LASER"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 10-1 to 10-1.

Wake vortices of aircraft landing at Heathrow have been measured with a coherent laser radar. Analysis of the vortex velocity profiles from B747 aircraft shows a series of symmetrical dips or inversions on approach to the central core. Such inversions are not predicted theoretically and contrast with the uniformly increasing velocity profiles observed from other aircraft. Vortex trajectories may also be reconstructed; in one case a B747 vortex, after initial descent, returned to the glideslope with undiminished strength over a minute later.

Vaughan, J. M., Steinvall, K. O., Werner, C. and Flamant, P. H.

"COHERENT LASER RADAR IN EUROPE"

IEEE Proceedings, Vol. 84, No. 2, February 1996, pp. 205-226

European work in coherent laser radar with 10 micron and shorter wavelength lasers is reviewed. Fundamental aspects include heterodyne studies of signal statistics and fluctuations, and detailed

experimental and theoretical work on signal amplification and autodyne arrangements with light reinjected into the laser cavity. Progress with lasers, detectors, and modulators has led to the development of several compact robust field systems both continuous-wave and pulsed. Various ground-based programs are described including local wind field measurement and wake vortex investigation at airfields, and study of range, image, and Doppler shift of hard targets. Airborne systems have investigated avionics problems of true airspeed, pressure error, and wind shear warning. Other airborne studies include ground imaging, obstacle warning, terrain following, and a compendium of atmospheric backscattering over the North and South Atlantic. In recent years, the European Space Agency has supported studies and technology development for a space-borne wind lidar in the Atmospheric Laser Doppler Instrument (ALADIN) program.

Vechtel, D.

"FLIGHT SIMULATOR STUDY ON THE INFLUENCE OF VORTEX CURVATURE ON WAKE ENCOUNTER HAZARD USING LES WIND FIELDS"

The Aeronautical Journal, Vol. 116, No. 1177, March 2012, pp. 287-302.

A flight simulator study has been carried out to evaluate the performance of modern flight control systems encountering curved wake vortices. During the decay process the shape of wake vortices alters significantly which has an influence on the encounter characteristics and thus on the encounter hazard. To analyze most realistic wake encounters, flow fields of matured vortices have been generated with large-eddy-simulations. These were used for the determination of induced force and moment histories during the encounter. The force and moment histories have been implemented into the equations of motions of a 6 DoF flight simulation. For the sake of comparison encounters have also been simulated with straight vortices as they were mostly used for many other investigations. The most important goal of the study was to analyze the difference between these ideally straight vortices and vortices with a more realistic shape regarding encounter acceptance. The simulator study was conducted in an A330 motion-based full-flight simulator with pilots-in-the-loop. The analyzed scenario was a wake encounter during final approach. The encounter conditions corresponded to a heavy-behind-heavy situation for IFR operations. The aircraft was flown either manually (in normal law) or with autopilot engaged. Altogether 93 encounters have been simulated, 38 with straight and 55 encounters with curved vortices. For encounters under manual control the simulator study revealed a potential risk of pilot induced oscillations during encounters with curved vortices. With autopilot engaged not even one encounter with curved vortices was classified to be unacceptable. Although significant aircraft response was experienced the autopilot never disengaged automatically in any encounter. Altogether about 12 percent of the encounters were not accepted by the pilots. This is indeed a significant number, especially as the analyzed scenarios can be regarded to be realistic situations which can occur in reality even if the applicable separation distances are applied.

Vechtel, D.

"SIMULATION STUDY OF WAKE ENCOUNTERS WITH STRAIGHT AND DEFORMED VORTICES"

The Aeronautical Journal, Vol. 120, No. 1226, April 2016, pp. 651-674.

A simulation study was conducted to investigate the influence of vortex deformation on wake encounter characteristics. Wake vortices tend to be strongly deformed during the decay process, depending on the atmospheric conditions in terms of turbulence and thermal stratification. For quantification of the influence of vortex deformation, encounters of an aircraft of the 'Medium' category behind a generator aircraft of the 'Heavy' category were simulated with straight vortices and with realistically deformed vortices derived from large-eddy simulations. All relevant parameters that influence the encounter characteristics, such as encounter angles and positions, were varied within a wide range. In order to cover all kinds of vortex deformation, encounters with different vortex ages from 16-136 seconds were simulated. Hence, all relevant phases during the vortex decay from nearly straight and wavy vortices to vortex rings were considered. The parameter variation study revealed that on average the impact on the encountering aircraft is less with deformed vortices than with straight vortices of comparable strength. Especially with vortex rings, the encountering aircraft is exposed to a much smaller impact. However, the results also show a larger aircraft response during encounters with wavy vortices just prior to vortex linking. The maximum aircraft response with wavy vortices is stronger than with straight vortices of comparable strength. Also, the strongest encounters occur under greater encounter angles with deformed vortices than with straight ones.

Vechtel, D.

"IN-FLIGHT SIMULATION OF WAKE ENCOUNTERS USING DEFORMED VORTICES"

Aeronautical Journal, Vol. 117, No. 1196, October 2013, pp. 997-1018.

During the decay process the shape of wake vortices changes significantly which has an influence on the encounter characteristics, hence on the encounter hazard. To evaluate the influence of vortex deformation on the wake encounter hazard, in-flight simulations with the DLR research aircraft ATTAS were carried out. For a realistic analysis of wake encounters flow fields of matured vortices were generated with large eddy simulations. These flow fields were used for the determination of histories of induced forces and moments acting on the wake encountering aircraft. The force and moment histories were then fed into the equations of motions of the non-linear six degree-of-freedom in-flight simulation of the DLR research aircraft ATTAS. To compare different stages of vortex deformation, encounters were simulated in flight with wavy vortices and vortex rings. The most important benefit of the in-flight simulation is the realistic environment, which enables a realistic assessment of pilots' encounter acceptance. The analyzed scenario was of a wake encounter during final approach. The encounter conditions correspond to separation distances of about 4nm and 5nm behind an aircraft of the 'heavy' category. During the encounters the ATTAS was flown under manual control. Altogether 31 encounters were simulated in flight, 9 with wavy vortices and 22 with vortex rings. The analysis of the results shows that with increasing vortex deformation the encounter impact acts increasingly in all degrees of freedom. Apparently, pilots assess roll-dominated encounters as more dangerous, which is why the unacceptability threshold is higher for encounters with vortex rings than for those with wavy vortices. Besides this unacceptability boundary, a harmlessness boundary can be determined, which seems to be independent from the degree of vortex deformation. This is an important outcome of the flight test described in this paper. Although, due to the very limited number of flight tests performed,

no clear correlation between the pilot ratings and objective measures could be assessed, an acceptance boundary for the roll control ratio could be determined below which the effects of vortex deformation seem to be negligible.

Vechtel, D., Stephan, A. and Holzaepfel, F.

"SIMULATION STUDY OF SEVERITY AND MITIGATION OF WAKE-VORTEX ENCOUNTERS IN GROUND PROXIMITY"

Journal of Aircraft, Vol. 54, No. 5, September-October 2017, pp. 1802-1813.

Wake-vortex encounter reports as well as simulations show a significantly higher encounter probability during landing shortly before touchdown in comparison to other flight phases. This is caused, among other factors, by the special behavior of wake vortices in ground effect. Nevertheless, hazardous wake encounters with adverse consequences are rarely reported. To gain more insight in the mechanisms of wake encounters close to ground, encounter simulations were performed with realistic vortex flowfields. These were generated using coupled Reynolds-averaged Navier-Stokes and large-eddy simulations covering the whole vortex evolution in ground effect from generation until decay and were used for a hazard analysis. Encounter simulations were performed with a simulation model of an A320-size aircraft with autopilot engaged following an A340-size aircraft. Different wind conditions and vortex ages were considered as well as a so-called plate line. Recent studies showed increased vortex decay when a series of plates is positioned in front of the runway threshold. The results of the study reveal a significant reduction of the maximal vortex impact on the encountering aircraft due to the plate line. This effect is more pronounced for younger vortices, but also for operationally relevant vortex ages, a considerable effect of the plate lines in reducing the maximum aircraft reaction due to a wake encounter close to the ground can be observed.

Veerman, H. C. M.

"PRELIMINARY MULTI-MISSION UAS DESIGN"

MS Thesis, August 2012, Delft University of Technology, Delft, Netherlands.

Unmanned vehicles are important when it comes to performing a desired task in a dangerous or inaccessible environment. Unmanned robots, have been successfully used for many years. More recently, a growing interest in Unmanned Aircraft Systems (UASs) has arisen. In the past few years, the development of sensors, microprocessors and propulsion systems resulted in UASs that are smaller, lighter, and more capable than ever before. This leads to endurance, efficiency and autonomy levels that exceed the capabilities of manned flight. Many successful designs have been created by several universities, commercial companies, and research agencies. Due to the wide variety of applications, several configurational concepts have been developed. As a result, most UAS designs are optimized for a dedicated task. To perform different tasks, users need to have access to multiple UASs. This means that manufacturers and users must maintain production and support lines for multiple UASs. The goal of this thesis was to create a preliminary design of a multi-mission UAS by using off-the-shelf systems.

This UAS must be able to perform both low and high-speed missions. To reach the stated goal a clear overview of all requirements had to be created first. This was followed by extensive market research to get an overview of the performance of current UAS designs. This market research was captured in a database. Based on the requirements in combination with the obtained database, all UAS classes and configurational options have been evaluated. The evaluation revealed that a new fixed wing electrically powered mini UAS design may be able to comply with the all UAS requirements. Based on the UAS database, weight estimation relationships for preliminary mini UAS design were derived. These relationships were used for the preliminary UAS performance and weight estimation. After investigating the technical and operational feasibility, the compliance with respect to the requirements was checked. This resulted in a new UAS design point. Subsequently, the UAS design was analyzed in more detail. Optimization of the wing was performed by using a quasi-3D optimizer. This was followed by a tail design that was based on UAS reference data and volume coefficients. The resulting wing and tail design were evaluated by investigating the wing-tail effects and the primary static & dynamic stability derivatives. This was followed by an evaluation of the material options for the structure. During this evaluation a new manufacturing technique, 3D printing, was tested. Subsequently, the propulsion system design was performed by using a UAV Propulsion Development Kit (UPDK). This UPDK can estimate the performance of multiple engine-propeller combinations. Based on the evaluation of the top five combinations, a combination was selected. Finally, the additional UAS subsystems were selected. After the preliminary UAS design was completed, the effectiveness of the design was evaluated. Together with off-the-shelf systems it was possible to create a design that is able to comply with most requirements. The WER for the payload weight was found to be inaccurate. This was caused by the fact that current UASs are equipped with heavier or additional payloads. The WER for the empty weight slightly underestimated the structural weight of the UAS. Overall, it can be concluded that it is possible to create a preliminary mini UAS design capable of performing both low and high speed missions using off-the-shelf systems.

Veillette, P. and Decker, R.

"BEWARE OF THE HORIZONTAL TORNADO! WAKE VORTEX, PART I"

Air Line Pilot, Vol. 63, No. 1, February 1994, pp. 26-3.

This paper reviews the state of the art of wake vortex behavior based on the 1991 Wake Vortices Conference in Washington, DC. Accident statistics are reviewed and it was noted that air carrier aircraft are often involved both as vortex generators and encounters. Vortex motion in five stages of development is reviewed: vortex formation, vortex effect on the other vortex (sink rates), growth of the vortex rotational axis and wavelength disturbances, core growth and vortex distortion, and distorted vortex rings.

Veillette, P. and Decker, R.

"BEWARE OF THE HORIZONTAL TORNADO! WAKE VORTEX, PART II"

Air Line Pilot, Vol. 63, No. 2, February 1994, pp. 24-2.

This paper reviews aircraft configuration effects (aircraft speed, wingspan, weight, flap deflection, engine replacement, etc.) on vortex movement and decay. Effects on aircraft motion are described based on how an aircraft encounters a vortex: flying right into the vortex itself (along track), flying in between a vortex pair, and flying perpendicular to a pair of vortices (cross track).

Veillette, P. R.

"DATA SHOWS THAT U.S. WAKE-TURBULENCE ACCIDENTS ARE MOST FREQUENT AT LOW ALTITUDE AND DURING APPROACH AND LANDING"

Flight Safety Digest, Vol. 21, No. 3-4, March-April 2002, pp. 1-47

In wake-turbulence accidents and incidents from 1983 through 2000, about 10 percent of the aircraft weighed more than 30,000 pounds/13,600 kilograms, and two-thirds of the pilots held commercial pilot certificates or airline transport pilot certificates.

Veillette, P. R. and Decker, R.

"HANDLING HORIZONTAL TORNADOES"

FAA Aviation Safety Journal., Vol. 13, Nos. 13 and 14, July 1993, pp. 3-9.

Wake vortices do not always behave in the orderly manner prescribed in the AIM, and what we have been told about avoiding them could actually get us into trouble. This report is an up-to-date briefing on the invisible menace.

Velarde, J.-M., Connors, J. N., Berry, M., Ali, M. Y. and Glauser, M. N.

"EXPERIMENTAL CHARACTERIZATION OF UAS FLOW FIELDS THROUGH HOTWIRE ANEMOMETRY AND PIV"

AIAA Paper 2018-4121, June 2018, Atlanta, GA.

The velocity flow field around a small unmanned air system (UAS), specifically the DJI Phantom 3, is investigated in a series of experiments at Syracuse University. Experiments were conducted in the 15'x10'x18' room herein referred to as the Indoor Flow Lab. The goal of these experiments was to gain a better understanding of the rich, turbulent flow field that a typical UAS creates. Characterization of the flow using hotwire anemometry and stereo particle image velocimetry (PIV) has been conducted. Regions of investigation include the downwash, above the vehicle, and far downstream. Investigation of several locations around the UAS show that dominant frequencies exist within the flow field. Analysis of the flow field includes calculation of mean velocities, turbulence intensities, mean-square velocity, and turbulent kinetic energy at several downstream locations. The spectral content of the flow field is analyzed and presented using power spectral density. Discussion and comparison of the applicability of hotwire anemometry and stereo-PIV to this flow will be made.

Veldhuis, L. L. M. and de Kat, R.

"VORTEX WAKE INVESTIGATION BEHIND A WING-FLAP MODEL WITH JET SIMULATION"

ICAS 2008, Anchorage, AK, Sept. 2008.

To get a better insight in the effect of jets on vortex development and decay, stereo-PIV measurements were performed in a towing tank behind a flapped aircraft model. The experimental data set yields the wake vortex behavior in a range that extends from the vortex formation stage up to the mid-field (approximately $t=2$ corresponding to 100 wingspans for angle of attack of 0 degrees and 60 wingspans for angle of attack of 6 degrees). Although the jet does not affect the overall circulation strength, it has a significant effect on the velocity distribution in the wake. A new Double Gaussian vortex model is introduced that perfectly fits the measurement data.

Veldhuis, L. L. M. and de Kat, R.

"VORTEX WAKE INVESTIGATION BEHIND A WING-FLAP MODEL WITH JET SIMULATION"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

In the current research we focus on the effect of jets on the development and decay of the vortices produced by a wing with flaps deployed, as typically found during take-off and landing. For this purpose wake vortex flow experiments were performed behind a generic aircraft model using the Stereo-PIV measurement technique in a towing tank.

Veldhuis, L. L. M. and Rentema, D. W. E.

"EXPERIMENTAL ANALYSIS OF THE VORTEX WAKE STRUCTURE BEHIND A PROPELLER-WING CONFIGURATION"

Proceedings of 78th Fluid Dynamics Panel Symposium, Characterization and Modification of Wakes from Lift: Vehicles in Fluids, AGARD, CP-584, Trondheim, Norway, May 1996, pp. 15-1 to 15-17.

A flow field survey was performed with a 5-hole pressure probe at 1 chord length behind a propeller-wing configuration revealing important qualitative and quantitative information on the propeller dominated interactive flow field. The model, that consists of a low aspect ratio semi-span wing model combined with a 4 bladed tractor propeller, was tested at several low subsonic flow conditions in the Delft University Low Speed Windtunnel. The distribution of total pressure and axial vorticity show, besides the well-known spiral tip vortex, a strong deformation of the slipstream structure. The deformation of the vortex wake is strongly related to the spanwise lift distribution of the propeller/wing configuration which might be used as a starting point for prediction of vortex formation and decay. It also determines the magnitude of the overall induced drag and the deformation process therefore has implications for the proper modeling of slipstreams used within theoretical prediction

codes for the analysis of airplane performance. To obtain quantitative information from the field data the theory of Betz and Maskell was applied to determine the lift, the profile drag and the induced drag for both the model with and without running propeller. Comparison of these results with external balance measurements shows a good agreement.

Veldhuis, L. L. M., de Kat, R. and Elsinga, G. E.

"TOWING TANK EXPERIMENTS OF COLD JET-VORTEX INTERACTION ON A GENERIC WING-FLAP MODEL"

AST4-CT-2005-012238, Delft Univ. of Technology, Delft, The Netherlands, December 2006

The main objective of the present study is to investigate the influence of a jet on the flap end vortex and the wake vortex formation. The investigation focuses on the direct influence of the jet on the flap end vortex and the (merged) vortex characteristics in the near to mid field. The main vortex characteristics addressed in this report are: the vortex trajectory, the maximum tangential velocity, the peak vorticity, and the vortex core radius. With respect to the jet negligible effects were found for the main parameters like circulation and vortex core growth. However, a significant effect emerged for the merging process of the flap end and tip vortex. This leads to noticeable effects on the tangential velocity distribution which in turn determine the induced rolling moment for follower aircraft. Whereas known vortex models in general fail to fit experimental data of double vortex systems, the Double Gaussian model developed and applied in this investigation, leads to accurate fits with the velocity distributions.

Veldhuis, L. L. M., Scarano, F. and Van Wijk, C.

"VORTEX WAKE INVESTIGATION OF AN AIRBUS A340 MODEL USING PIV IN A TOWING TANK"

AIAA Paper No. 2003-3814, Orlando, FL, June 2003

PIV wake-measurements in a towing tank on a 1/48 scaled model of an Airbus A340-300 towed at a speed of 3 and 5 m/s with angles of attack of 2 degrees, 4 degrees, 8 degrees, are discussed. The main objective of the investigation is to demonstrate the applicability of PIV diagnostics in wake vortex research in towing tank facilities. The experiments are performed in a fixed plane perpendicular to the towing direction to measure the streamwise component of the wake vorticity. An underwater moving camera device (traversing-field-of-view or TFOV) is used to keep the moving vortex in the field of view during the vortex whole downward motion. The TFOV method is proposed as a cost-effective solution to the option of camera clusters and minimal efforts are needed for the calibration of the field of view. The measurement yields the wake vortex behavior described during a period that extends from the vortex formation stage up to the mid-field (200 wingspans). The results obtained show that relevant vortex parameters, like vortex trajectory, tangential velocity, peak vorticity, and vortex core radius, can be obtained with the PIV technique both in a global (trajectories) and detailed sense (decay parameters).

Veldhuis, L. L. M., van Wijk, K. and Scarano, F.

"PIV-SURVEY OF THE VORTEX WAKE STRUCTURE BEHIND AN AIRBUS A340 IN A TOWING TANK"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001.

To find detailed information about the vortex structure and its decay, PIV measurements were performed in a 142 m long water tank behind an Airbus A340-300 model. The main objective of the experimental investigations is to demonstrate the applicability of the PIV technique for measuring the mid to far field behind aircraft in towing tank facilities. The collected data are used within the European research program C-WAKE to arrive at a better understanding of the behavior of the vortex system at large distance behind the aircraft. The survey was performed at a 2-, 4- and 8-degree angle of attack and towing speeds of 3 m/s and 5 m/s. Two-dimensional PIV data were taken in a fixed plane perpendicular to the towing direction to measure the stream wise wake vorticity. To be able to track the down going vortices an underwater camera moving vertically with the vortices was used yielding high spatial resolution measurements. Recordings are acquired at an effective rate of 3.3 Hz over a field of view of about 0.5 x 1.2 square meters. The image analysis was performed with an iterative PIV processing technique with multigrid interrogation including a window distortion algorithm. The collected data on the vortex flow demonstrate that the PIV technique is very suitable for this type of experimental research. Moreover, the application of the towing tank facility in conjunction with PIV diagnostics allows to obtain a longer time/space description of the vortex wake (up to 260 wingspans) in comparison with wind tunnel experiments and catapult facilities.

Veldhuis, L., Voskuil, M. and Fransen, B.

"FORMATION FLIGHT -- FINE-TUNING OF THEORETICAL PERFORMANCE PREDICTION"

AIAA Paper 2013-0961, January 2013, Grapevine, TX.

In this paper we address the theoretical analysis of commercial aircraft formation flight. To investigate the usefulness of wind tunnel tests for detailed analysis of the flow phenomena associated with formation flight of commercial aircraft, the problem is revisited and extended where appropriate. For this purpose, an enhanced mathematical model was developed that allows the investigation of formation flight aspects not yet covered by previous studies. This model is based on a vortex lattice approach which includes a selection of various vortex models as well as the effects of wind tunnel walls and Reynolds number scaling. A formation of two and three aircraft is considered with a separation distance of 10 to 100 spans. It is demonstrated that in some earlier simulations, discussed in open literature, an incorrect lift coefficient is used which leads to erroneous prediction of the induced drag reductions. The application of positive sweep, taper and winglets are all found to have beneficial effects on formation flight induced drag reduction, while aircraft trim causes a slight decrease of induced drag reduction. Furthermore, the wing aspect ratio was not found to have a significant influence. According to the calculation model, a typical medium aircraft exhibits a total drag reduction around 13 percent when flying behind an identical aircraft. Good agreement between scaled and full-scale simulation induced drag reduction is found in terms of both trend and induced drag reduction at the so-called

sweet spot. The addition of wind tunnel walls causes a large increase in maximum induced drag benefits, which signifies the need for accurate wind tunnel wall corrections in case of future wind tunnel tests.

Velkoff, H. R. and Terkel, H.

"NON-STEADY VELOCITY MEASUREMENT OF THE WAKE OF A HELICOPTER ROTOR AT LOW ADVANCED RATIOS"

ARO-14142.5-EX, Ohio State Univ., Columbus, OH, September 1981

A system was developed which could measure the instantaneous velocities in the wake of a model helicopter rotor operating at low advance ratios. A three-wire hot film probe was mounted on a traverse and placed at many positions in the wake. The output of the probe was fed into an on-line computer operating in an interactive mode. Computer generated vector plots were made of both time averaged velocities and instantaneous velocities for the case of $\mu = 0.06$.

Venkataramanan, S. and Dogan, A.

"DYNAMIC EFFECTS OF TRAILING VORTEX WITH TURBULENCE AND TIME-VARYING INERTIA IN AERIAL REFUELING"

AIAA Paper No. 2004-4945, Providence, RI, August 2004

This paper describes the dynamic modeling of a receiver aircraft undergoing an aerial refueling, including the effect of time-varying mass and inertia properties associated with the fuel transfer, the tanker's vortex induced wind effect and atmospheric turbulence. Three significant refueling effects due to the fuel transfer that have been studied in our model are (i) the continuous mass change (ii) the change in the location of the receiver's center of mass and (iii) the change in the inertia matrix. A new set of nonlinear, 6-DOF, rigid body equations of motion including the wind effect in addition to the above-mentioned effects of fuel transfer, are derived for the receiver aircraft. The assumption of the existence of plane of symmetry is also relaxed for the receiver aircraft, to cater to situations of asymmetric fuel loading. The effect of the aerodynamic disturbances induced on the receiver, due to the tanker's vortices as well as turbulence, are modeled using an averaging technique that computes the effective wind components and gradients from the induced wind velocity distribution. Engine and actuator dynamics are also incorporated into our aircraft dynamic model. The receiver aircraft before fuel transfer is treated as a rigid body made up of 'n' particles. The dynamic effects due to fuel transfer are modeled by considering the mass change to be confined only to a finite number ('k') of lumped masses. These lumped masses would normally represent the fuel tanks on the receiver aircraft. Hence, once the refueling begins, the mass of the individual lumped masses and the location of the CM of the whole receiver aircraft are calculated using the design parameters such as the shape, size, location of the individual fuel tank and the rate of fuel flowing into it.

Venkataramanan, S. and Dogan, A.

"MODELING OF AERODYNAMIC COUPLING BETWEEN AIRCRAFT IN CLOSE PROXIMITIES"

AIAA Paper 2004-5172, August 2004, Providence, RI.

A simulation-oriented technique is developed for modeling the aerodynamic coupling between aircraft flying close to each other. The velocities induced by the leading aircraft's vortex on the following aircraft are written as a function of both the relative separation in all the three axial directions and the relative orientation between the two aircraft. These non-uniform vortex-induced wind and wind gradients acting over the trail aircraft are approximated with uniform effective wind and wind gradients that can be directly used in standard equations of motion without having to explicitly compute the induced forces and moments. Thus, the vortex effect modeling on the follower's dynamics is made more naturally adaptable to a wide variety of computer simulations involving multi-aircraft close proximate flight. Several vortex models that were employed to estimate the vortex induced velocities and the various averaging schemes that were applied to compute the effective wind components and gradients are explained. The comparison analysis performed using the wind tunnel measurements for the formation flight of two aircraft shows that the plots of incremental coefficients of the forces and moments induced on the follower aircraft exhibit an improved match over those shown in our earlier work. Finally, the scope for the application of our technique in the contexts of formation flight and aerial refueling, is outlined.

Venkataramanan, S., Dogan, A. and Blake, W.

"VORTEX EFFECT MODELLING IN AIRCRAFT FORMATION FLIGHT"

AIAA Paper No. 2003-5385, Austin, TX, August 2003

This study develops a new technique for the vortex effect modeling and incorporates it in a six-DOF analysis of a close formation flight. The velocities induced by the leader's vortex on the following aircraft are written as a function of the relative separation in all the three axial directions and also the relative orientation between the leader and the follower aircraft (characterized by the rotation matrices) using a modified horseshoe vortex model based on Helmholtz profile. Since the induced wind and wind gradient vary along the span and length of the aircraft, an averaging technique is implemented to compute effective wind and wind gradient on the following aircraft. The effective wind components and gradients are introduced into the nonlinear aircraft equations that include components of wind and temporal variation of wind in the body frame to determine the effect on the follower's dynamics. The effect of vortex decay over time is also included in our model. Special care has been taken to accommodate different geometrical dimensions for the leader and the follower aircraft and to include many useful geometrical parameters of the aircraft like the wing sweep angle, the dihedral angle and the relative distance between the center of mass of the aircraft and the aerodynamic center of the wing, in estimating the vortex effect experienced during formation flight. A comparison study has been presented which shows that the induced forces and moments computed by our method match well with the wind tunnel measurements.

Venkatesh, T. N., Shameem, C. A. and Saravanakumar, J.

"STUDY OF A POSSIBLE WAKE VORTEX ENCOUNTER OF AN AIRCRAFT OVER THE ARABIAN SEA"

Fifteenth Asian Congress of Fluid Mechanics, published in IOP Journal of Physics Conf. Series, Vol. 822, 2017, pp. 012049-1 - 012049-7.

A Jet airways aircraft encountered severe turbulence over the Arabian sea. We have performed high-resolution numerical simulations of the weather conditions at the time of the incident to ascertain the possible cause of the incident: atmospheric clear-air turbulence or a wake vortex encounter. Our analysis of the turbulence indices and parameters related to vortex propagation/decay at the flight altitude, suggests that wake-vortex encounter was the more likely cause of the incident.

Veovodin, A. V.

"NUMERICAL INVESTIGATION OF THE EFFECT OF WINGLETS ON THE EVOLUTION OF AN AIRCRAFT VORTEX WAKE"

Fluid Dynamics, Vol. 43, No. 5, 2008, pp. 725-730.

The effects of winglets on the aerodynamic characteristics of a heavy aircraft and the parameters of the vortex wake behind it is investigated for the landing regime. The solution of the complete problem is obtained by breaking up the wake into three regions, namely, the near, intermediate, and far flowfields, in which the corresponding subproblems are successively solved. The wake flowfields are obtained at different distances from the aircraft, together with the distributions of the mean azimuthal velocity over the vortex radius, and the lifetime of the vortex system is estimated for several one- and two-element wingtip versions. All the results are compared with those for the baseline layout with no winglets.

Vera, M. and Linan, A.

"ON THE INTERACTION OF VORTICES WITH MIXING LAYERS"

Physics of Fluids, Vol. 16, No. 7, July 2004, pp. 2237-2254

We describe the perturbations introduced by two counter-rotating vortices, in a two-dimensional configuration or by a vortex ring in an axisymmetric configuration, to the mixing layer between two counterflowing gaseous fuel and air streams of the same density. The analysis is confined to the near stagnation point region, where the strain rate of the unperturbed velocity field, is uniform. We restrict our attention to cases where the typical distance between the vortices, or the characteristic vortex ring radius, is large compared to both the thickness of the vorticity core and the thickness of the mixing layer. In addition, we consider that the ratio of the vortex circulation to the kinematic viscosity is large compared to unity. Then, during the interaction time, the viscous and diffusion effects are confined to the thin vorticity core and the thin mixing layer, which, appears as a passive interface between the two counterflowing streams when they have the same density. In this case, the analysis provides a simple procedure to describe the displacement and distortion of the interface, as well as the time evolution of

the strain rate imposed on the mixing layer, which are needed to calculate the inner structure of the reacting mixing layer as well as the conditions for diffusion flame extinction and edge-flame propagation along the mixing layer. Although in the reacting case variable density effects due to heat release play an important role inside the mixing layer, in this paper the analysis of the inner structure is carried out using the constant density model, which provides good qualitative understanding of the mixing layer response.

Veram, S., Lozito, S., Kozon, T., Ballinger, D. and Resnick, H.

"PROCEDURES FOR OFF-NOMINAL CASES: VERY CLOSELY SPACED PARALLEL RUNWAY OPERATIONS"

27th Digital Avionics Systems Conf., St. Paul, Minnesota, Oct. 2008

This study investigated procedures to increase capacity in the terminal area using a high-fidelity flight deck simulator. The concept was developed to achieve visual meteorological condition capacities under instrument meteorological conditions when landing aircraft on runways 750 ft apart. The purpose was to investigate procedures related to breakout maneuvers on final approach during off-nominal conditions. Fifty percent of the simulation runs had an off-nominal situation. The off-nominal situation was either the wake of the lead aircraft drifting too close to the trailing aircraft or the lead aircraft deviating from its course and blundering towards the trailing aircraft. The location of the off-nominal situation was also a variable. Results showed that the workload and situational demands experienced by pilots were higher in the off-nominal as compared to the normal scenario. Pilots executed a breakout maneuver earlier for wake intrusion than for aircraft deviation. The location and cause of the off-nominal situation did not have a significant impact on workload or situation awareness. In general, the pilots flew the breakout maneuver accurately and safely. The results provide an assessment of the procedures for breakout maneuvers during off-nominal conditions.

Vergine, F., Ground, C. and Maddalena, L.

"TURBULENT KINETIC ENERGY DECAY IN SUPERSONIC STREAMWISE INTERACTING VORTICES"

Journal of Fluid Mechanics, Vol. 807, 2016, pp. 353-385.

Only a few fundamental studies on the dynamics and interactions of supersonic streamwise vortices have been conducted so far despite the recognized potential of these structures to enhance supersonic mixing. In an effort to shed light on this largely unexplored field, multiple experimental campaigns were conducted in a Mach 2.5 flow to probe the dynamics of turbulent decay in complex flows originating from selected modes of supersonic streamwise vortex interaction. The first part of the manuscript presents the detailed study of two vortex interaction scenarios: one selected to obtain merging of co-rotating vortices and the other to prevent vorticity amalgamation. In the second part, data from three additional vortex merging cases are used to substantiate the findings of the first part of the study and characterize the decay of turbulence. Stereoscopic particle image velocimetry was employed to probe the resulting flow fields at different downstream stations. It was found that these complex vortex interactions measurably affect both the morphology and the magnitude of the

streamwise vorticity and turbulent kinetic energy as well as the associated decays. Particularly, while the turbulent kinetic energy across each vorticity patch undergoes an initial production before decreasing monotonically in both scenarios, its content in the coalesced structure is roughly double that of the isolated vortices. The manuscript also presents the analysis of the turbulence data from 27 supersonic vortical structures differing in shape, strength and modes of interaction, acquired within a range of vortex Reynolds numbers of almost one order of magnitude. Dimensional analysis was then used to correlate the spatial decay of turbulent kinetic energy with the vortex Reynolds number. For all the cases considered here, where the fluctuating Mach number was found to be subsonic, the form of the resulting law was like that reported in previous scholarly publications, despite the complexity of the vortex dynamics considered in this work.

Verma, S., Lozito, S., Kaneshige, J., Ballinger, D., Sharma, S., Martin, L., Kozon, T., Cheng, L. and Subramanian, S.

"INTEGRATED PILOT AND CONTROLLER PROCEDURES: AIRCRAFT PAIRING FOR SIMULTANEOUS APPROACHES TO CLOSELY SPACED PARALLEL RUNWAYS"

Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), June 2011, Berlin, Germany.

Parallel runway operations have been found to increase capacity within the National Airspace but poor visibility conditions reduce the use of these operations. Previous research examined the concepts and procedures related to parallel runways; however, there has been no investigation of the procedures associated with the strategic and tactical pairing of aircraft for these operations. This study developed and examined the pilot and controller procedures and information requirements for creating aircraft pairs for parallel runway operations. The goal was to achieve aircraft pairing with a temporal separation of 15s (+/- 10s error) at a 'coupling' point that was about 12nmi from the runway threshold. Two variables were explored for the pilot participants: two levels of flight deck automation (current-day flight deck automation and auto speed control future automation) as well as two flight deck displays that assisted in pilot conformance monitoring. The controllers were also provided with automation to help create and maintain aircraft pairs. Results show the operations in this study were acceptable and safe. Subjective workload, when using the pairing procedures and tools, was generally low for both controllers and pilots, and situation awareness was typically moderate to high. Pilot workload was influenced by display type and automation condition.

Verma, S., Lozito, S., Kozon, T., Ballinger, D. and Resnick, H.

"PROCEDURES FOR OFF-NOMINAL CASES: VERY CLOSELY SPACED PARALLEL RUNWAY OPERATIONS"

IEEE/AIAA 27th Digital Avionics Systems Conference, October 2008, St. Paul, Minnesota.

This study investigated procedures to increase capacity in the terminal area using a high-fidelity flight deck simulator. The concept was developed to achieve visual meteorological condition capacities under instrument meteorological conditions when landing aircraft on runways 750 ft apart. The purpose was

to investigate procedures related to breakout maneuvers on final approach during off-nominal conditions. Fifty percent of the simulation runs has an off-nominal situation. The off-nominal situation was either the wake of the lead aircraft drifting too close to the trailing aircraft or the lead aircraft deviating from its course and blundering towards the trailing aircraft. The location of the off-nominal situation was also a variable. Results showed that the workload and situational demands experienced by pilots were higher in the off-nominal as compared to the normal scenario. Pilots executed a breakout maneuver earlier for wake intrusion than for aircraft deviation. The location and cause of the off-nominal situation did not have a significant impact on workload or situation awareness. In general, the pilots flew the breakout maneuver accurately and safely. The results provide an assessment of the procedures for breakout maneuvers during off-nominal conditions.

Vermeer, L. J., Sorensen, J. N. and Crespo, A.

"WIND TURBINE WAKE AERODYNAMICS"

Progress in Aerospace Sciences, Vol. 39, 2003, pp. 467-510.

The aerodynamics of horizontal axis wind turbine wakes is studied. The contents is directed towards the physics of power extraction by wind turbines and reviews both the near and far wake region. For the near wake, the survey is restricted to uniform, steady and parallel flow conditions, thereby excluding wind shear, wind speed and rotor setting changes and yawed conditions. The emphasis is put on measurements in controlled conditions. For the far wake, the survey focusses on both single turbines and wind farm effects, and the experimental and numerical work are reviewed; the main interest is to study how the far wake decays downstream, in order to estimate the effect produced in downstream turbines. The article is further restricted to horizontal axis wind turbines and excludes all other types of turbines.

Verstraeten, J. G. and Slingerland, R.

"DRAG CHARACTERISTICS FOR OPTIMALLY SPAN-LOADED PLANAR, WINGLETTED, AND C WINGS"

Journal of Aircraft, Vol. 46, No. 3, May-June 2009, pp. 962-971.

This paper focuses on the drag characteristics of optimally span-loaded, wingletted, and C wings. The span load is optimized resulting in minimum induced or total drag. The wing-root bending moment is kept constant for all analyzed wings to ascertain that different wings have comparable weight. The optimum span loadings for the different types of wing are calculated using a fast and simple numerical method. The wings are analyzed in the Trefftz plane, infinitely far behind the wing. Lagrange multipliers are used to calculate the optimum span loading resulting in minimum induced or total drag, with the wing-root bending moment and/or the lift coefficient as constraint. The induced drag can be calculated using the optimum span loading. The profile drag is assumed to be a function of the local lift coefficient. The results indicate that the C wing does not have real aerodynamic performance advantages compared to a wingletted wing. For wings with span and/or aspect ratio constraints, a winglet offers a drag reduction relative to a planar wing.

Verstynen, Jr., H. A.

"NASA FLIGHT RESEARCH ON AIRCRAFT WAKE VORTICES AND MINIMIZATION CONCEPTS"

AIAA Paper No. 1974-0953, Los Angeles, CA, 1974

A summary of NACA and NASA wake vortex flight research is presented with selected data from some tests. A brief review of current NASA wake vortex programs is given and a preview of potential future flight tests in the wake vortex area.

Verstynen, Jr., H. A. and Dunham, Jr., E. R.

"A FLIGHT INVESTIGATION OF THE TRAILING VORTICES GENERATED BY A JUMBO JET TRANSPORT"

NASA TN D-7172, April 1973, NASA Langley Research Center, Hampton, VA.

A flight investigation has been conducted to study the velocity and persistence characteristics of the trailing vortices generated by a jumbo jet transport. The investigation showed that the tangential velocities were initially higher for vortices generated with the flaps up and that they persisted for longer distances behind the aircraft than those generated with the flaps down. The core radii with flaps down appeared to be generally larger than those with flaps up.

Verstynen, Jr., H. A. and Patterson, Jr., J. C.

"PRELIMINARY FLIGHT TEST INVESTIGATION OF AN AIRBORNE WAKE VORTEX DETECTION CONCEPT"

AIAA Paper No. 1990-1282, Ontario, CA, May 1990.

One means to help reduce vortex-limited minimum in-trail separations might be to provide pilots with onboard sensors capable of detecting impending vortex encounters and provide warnings and recommended avoidance maneuvers. Preliminary results of a flight test indicate that measured maximum detection distances using wingtip-mounted flow angularity vanes are slightly lower than predicted.

Verzicco, R., lafrati, A., Riccardi, G. and Fatica, M.

"ANALYSIS OF THE SOUND GENERATED BY THE PAIRING OF TWO AXISYMMETRIC CO-ROTATING VORTEX RINGS"

Journal of Sound and Vibration, Vol. 200, Issue 3, February 1997, pp. 347-358.

The pairing of two axisymmetric co-rotating vortex rings is considered as a model problem for the interaction of the large-scale structures in round jets. By using direct numerical simulations of the incompressible Navier-Stokes equations, the sound radiation of the interaction has been analyzed, with

consideration of the effects of the Reynolds number and initial thickness of the rings. The acoustic signature of the interaction has revealed only minor effects of the Reynolds number. But the signature shows large effects of the vorticity distribution, with the eventual appearance of a secondary frequency.

Vetel, J., Garon, A. and Pelletier, D.

"VORTEX IDENTIFICATION METHODS BASED ON TEMPORAL SIGNAL-PROCESSING OF TIME-RESOLVED PIV DATA"

Exp. Fluids, Vol. 48, 2010, pp. 441-459.

The lack of a universally accepted mathematical definition of a vortex structure has led to a considerable number of Eulerian criteria to identify coherent structures. Most are derived from the instantaneous local velocity gradient tensor and its derivatives and require appropriate thresholds to extract the boundaries of the structures. Notwithstanding their great potential for studying coherent structures, most criteria are not frame-independent and they lack a clear physical meaning. The Lyapunov exponent, a popular tool in dynamical system theory, appears as a promising alternative. This Lagrangian criterion does not suffer from the drawbacks of the Eulerian criteria and is constructed on a simple physical interpretation that includes information on the history of the flow. However, since the computation of the Lyapunov exponent involves the knowledge of fluid particle trajectories, experimental applications are currently restricted to laminar flows and two-dimensional turbulence, if velocity fields are time-resolved. In this work, we explore temporal post-treatment methods to extract vortical structures developing in a flow through a smooth axisymmetric constriction. Data from planar time-resolved Particle image velocimetry, measuring two or three components of the velocity vectors, are transformed via the Taylor hypothesis to quasi-instantaneous three-dimensional velocity field and are interpreted in terms of the discrete wavelet decomposition, the finite-time Lyapunov exponent, and the linear stochastic estimation. It appears that these methods can concurrently provide very rich and complementary scalar fields representing the effects of the vortical structures and their interactions in the flow.

Vey, S., Paschereit, O. C., Greenblatt, D. and Meyer, R.

"FLAP VORTEX MANAGEMENT BY ACTIVE GURNEY FLAPS"

AIAA Paper No. 2008-286, Reno, NV, January 2008

An experimental study was conducted to assess the applicability of limited span Gurney flaps for altering the flap-edge vortex characteristics of a swept constant chord half model with a commercial aircraft airfoil and high lift system (slat and flap). Phase one of the study involved the testing of static Gurney flaps mounted at the trailing-edge and flap-edge where different flap heights and fractions of flap span were evaluated. Data acquisition included PIV measurements downstream of the flap-edge, six-component load measurements and surface pressure measurement on the main-element and in the flap-edge region. The Gurney flaps produced significant variation of the vortex centroids, up to 3.49%

of the semi-span (8.69% of chord) with corresponding small changes to overall lift coefficient and overall drag coefficient. The strategy employed was based on the vortex roll-up relations of Betz, as modified for flapped wings by Donaldson. Phase two of this study, involved the evaluation of dynamically deployed Gurney flaps, where phase-averaged PIV measurements were made of the vortex trailing the flap. This was motivated by the desire to periodically perturb the vortex centroids, with a view to exciting wake instabilities and thus triggering a faster decay. When driving the Gurney flap and hence perturbing the vortices at wavelengths smaller than or greater than the wingspan, the authority over the vortex centroids did not materially diminish.

Vickers, T. K.

"LIVING WITH VORTICES"

The Controller, Vol. 4, January 1965, pp. 6-13

Summary of the most important facts which have been learned about the generation and behavior of trailing vortices. Large aircraft generate turbulent wakes which can be hazardous to small aircraft encountering them. Factors affecting vortex intensity are weight of the aircraft, the load factor, wingspan, air speed, and air density. Vortex rotation, wake movement, helicopter vortices, and vortex dissipation are discussed. Factors involved when an aircraft penetrates a vortex are examined, and various ways of avoiding vortices are presented.

Vickers, T. K.

"ATC IMPLICATIONS OF THE 747 SP"

Journal of the Acoustical Society, Vol. 51, No. 1, January 1972, pp. 206-209.

This year Boeing is shrinking the 747 design to create a more compact, lighter, long-range wide-body transport, the 747 SP. The reduced size combined with the same engines as used in the standard 747 will result in some spectacular increases in performance for the new aircraft. Most of these increases will directly benefit the ATC system. On flights up to 3000 miles in length the SP will lift off in only 25 seconds. Other improvements include a shorter takeoff runway length, a higher climb rate, and a higher cruising altitude. The advantages of these improvements are discussed along with the effects the design changes could have on the alleviation of the trailing vortex problem.

Vicroy, D. D.

"NASA WAKE ENCOUNTER FLIGHT TEST DATABASE"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

In the mid-nineties the National Aeronautics and Space Administration (NASA) began developing the Aircraft Vortex Spacing System (AVOSS) with the goal of improving airport capacity through improved

aircraft arrival spacing. The system involved a set of ground-based sensors used to forecast, detect and monitor vortices on the approach path. An initial requirement of this system was to establish a vortex decay threshold or boundary that defined how weak a vortex on the approach path must be for the in-trail aircraft to safely continue the approach. Developing a decay threshold required extensive use of wake vortex encounter simulations of a variety of aircraft. It was quickly noted that although several wake encounter simulation studies had been conducted since the mid-seventies, the wake encounter models used in the simulations were either not validated or validated purely on subjective pilot evaluation. This was primarily due to the lack of flight test data sufficient to validate the wake encounter simulation models. To fill this void in test data NASA conducted a series of flight tests from 1995 through 1997 using a Lockheed C-130 as the wake generator and a Boeing B737-100 as the wake encounter aircraft. A modified North American Rockwell OV-10 Bronco was used to measure the wake, the atmospheric state and stereo video of the wake encounters. The goal of these tests was to provide a data set for validation of wake encounter simulation models and develop an improved understanding of wake vortex physics and atmospheric interaction. The test data has been compiled into an integrated database available to the wake vortex research community. This paper describes the wake vortex flight tests, the data processing, the database development and access, and results obtained from preliminary wake-characterization analysis using the data sets.

Vicroy, D. D. and Nguyen, T.

"A NUMERICAL SIMULATION STUDY TO DEVELOP AN ACCEPTABLE WAKE ENCOUNTER BOUNDARY FOR A B737-100 AIRPLANE"

AIAA Paper No. 1996-3372, San Diego, CA, July 1996

NASA is conducting research with the goal of enabling safe improvements in the capacity of the nation's air transportation system. The wake-vortex upset hazard is an important factor in establishing the minimum safe spacing between aircraft during landing and take-off operations, thus impacting airport capacity. A batch simulation study was conducted to assess the sensitivity of various safe landing criteria in the development of an acceptable wake encounter boundary. A baseline six-degree-of-freedom simulation of a B-737-100 airplane was modified to include a wake model and the vortex-induced forces and moments. The guidance and control input for the airplane was provided by an auto-land system. The wake strength and encounter geometry were varied. A sensitivity study was also conducted to assess the effects of encounter modeling methods and accuracy.

Vicroy, D. D., Brandon, J., Greene, G. C., Rivers, R. A., Shah, G., Stewart, E. C., and Stuever, R. R.

"CHARACTERIZING THE HAZARD OF A WAKE VORTEX ENCOUNTER"

AIAA Paper No. 1997-0055, Reno, NV, January 1997

The National Aeronautics and Space Administration (NASA) is conducting research with the goal of enabling safe improvements in the capacity of the nation's air transportation system. The wake vortex upset hazard is an important factor in establishing the minimum safe spacing between aircraft during

landing and take-off operations, thus impacting airport capacity. Static and free-flight wind tunnel tests and flight tests have provided an extensive data set for improved understanding of vortex encounter dynamics and simulation. Piloted and batch simulation studies are also ongoing to establish a first-order hazard metric and determine the limits of an operationally acceptable wake induced upset. This paper outlines NASA's research in these areas.

Vicroy, D. D., Brandon, J., Greene, G. C., Rivers, R. A., Shah, G., Stewart, E. C., Stuever, R. R. and Rossow, V. J.

"WAKE VORTEX ENCOUNTER MODEL VALIDATION EXPERIMENTS"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206235, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 371-383

The goal of this current research is to establish a database that validate/calibrate wake encounter analysis methods for fleet-wide application; and measure/document atmospheric effects on wake decay. Two kinds of experiments, wind tunnel experiments and flight experiments, are performed. This paper discusses the different types of tests and compares their wake velocity measurement.

Vicroy, D. D., Stuever, R. A., Stewart, E. C. and Rivers, R. A.

"FLIGHT DATA REDUCTION OF WAKE VELOCITY MEASUREMENTS USING AN INSTRUMENTED OV-10 AIRPLANE"

NASA/TM-1999-209552, July 1999, NASA Langley Research Center, Hampton, VA

A series of flight tests to measure the wake of a Lockheed C-130 airplane and the accompanying atmospheric state have been conducted. A specially instrumented North American Rockwell OV-10 airplane was used to measure the wake and atmospheric conditions. An integrated database has been compiled for wake characterization and validation of wake vortex computational models. This paper describes the wake-measurement flight-data reduction process.

Vicroy, D. D., Vijgen, P. M., Reimer, H. M., Gallegos, J. L. and Spalart, P. R.

"RECENT NASA WAKE-VORTEX FLIGHT TESTS, FLOW-PHYSICS DATABASE AND WAKE-DEVELOPMENT ANALYSIS"

SAE Paper 1998-5592, Anaheim, CA, September 1999.

A series of flight tests over the ocean of a four-engine turboprop airplane in the cruise configuration have provided a data set for improved understanding of wake vortex physics and atmospheric interaction. An integrated database has been compiled for wake-characterization and validation of wake-vortex computational models. This paper describes the wake-vortex flight tests, the data processing, the database development and access, and results obtained from preliminary wake-characterization analysis using the data sets.

Vicroy, D., Bowles, R., Brandon, J. M., Greene, G. C., Jordan, Jr., F. L., Rivers, R. A., Stewart, E. C., Stough, III, H. P. and Stuever, R. A.

"NASA WAKE VORTEX RESEARCH"

Proceedings of International Council of the Aeronautical Sciences, 19th Congress, Anaheim, CA, September 19-23, 1994, pp. 519-528

The National Aeronautics and Space Administration (NASA) is conducting research that will enable safe improvements in the capacity of the nation's air transportation system. The wake-vortex hazard is a factor in establishing the minimum safe spacing between aircraft during landing and take-off operations, thus impacting airport capacity. The ability to accurately model the wake hazard and determine safe separation distances for a wide range of aircraft, weather, and operational scenarios may provide the basis for significant increases in airport capacity. This paper describes the current and planned NASA research which is focused on increasing airport capacity by safely reducing wake-hazard-imposed aircraft separations through advances in several technologies including vortex motion and decay prediction, vortex encounter modeling, and wake-vortex detection.

Vid, V. I., Dedesh, V. T., Kiose, S. N., Tenishev, R. H., Pavlova, E. G., Kagarmanov, R. I., Popov, V. V., Rumyantseva, G. P., Lavrov, M. A., Enchilik, R. V., Grigoryev, M. A., Zamyatin, A. N., Voronich, L. V., Lanshin, A. I. and Evstigneev, A. A.

"ECOLOGICAL OPTIMIZATION OF JET AIRCRAFT FLIGHTS IN VIEW OF CONTRAILS AND CONTRAIL CIRRUS FORMATION"

ICAS 2014, September 2014, St. Petersburg, Russia.

Presented in the paper are the results of research carried out in the Gromov flight Research Institute in 2004-2013 on elaboration and approbation of calculation-experimental methodic of evaluation and prediction of formation and existence of condensation trails (contrails) and condensation cirrus clouds during flights of civil aviation jet aircraft and of methodology of ecological optimization of aircraft flights on concrete flight routes. As a result of the research conducted there were obtained and approved the quantitative indices determining a necessary and sufficient conditions of contrails and contrail cirrus formation and existence enabling to evaluate and forecast the ecological optimization of aircraft flights planning along flight routes with the aim to reduce the linear contrails and aviation induced cirrus clouds harmful influence on the Earth heat exchange -- 'greenhouse effect.

Vidal, A.

"OPERATIONAL CONCEPT AND SYSTEM REQUIREMENTS FOR AN ATC SYSTEM ALLOWING DYNAMIC WAKE VORTEX SEPARATIONS"

First Workshop WakeNet2-Europe, 'Wake Data and Safety Assessment Methods', London, November 2003.

Several technologies to detect and predict wake-vortex have been developed during the last years. These technologies are now quite mature and weather conditions in which wake vortices decay quickly can be identified and used reliably by 'wake vortex predictors'. There is potential for making the separation distances dependent on these predictors as well as aircraft weight. This could increase the capacity of airports in certain weather conditions. Nevertheless, none of these systems are connected to ATC providers (enroute, approach, tower and arrival/departure managers) and remain at the R&D stage. The ATC-WAKE project intends to develop and build an operational platform. For this purpose, the first step is: To define operational requirements; To define operational concepts and procedures; To update and refine the selected operational concepts and procedures; To define user requirements; To define the system requirements based on operational concepts and user requirements. The following issues have been addressed: Operational issues - need and use of WV information in the context of ATC operations, constraints and required supporting systems; Technical issues - high level interface to existing (legacy) ATC systems of WV targeted system. As a first step towards implementation of ATC-WAKE Facility, the system requirements have drawn the preliminary operational concept and the requirements for using separation minima based on WV detection and prediction information. During the next phase, the operational feasibility of the new integrated ATC system, including an analysis of the interoperability with existing ATC systems and the usability and acceptability by its foreseen end-users (air traffic controllers) will be evaluated. Following the definition of operational concepts and procedures, this will be realized through fast-time simulations with a total airspace and airport model.

Viecelli, J. A.

"STATISTICAL MECHANICS AND CORRELATION PROPERTIES OF A ROTATING TWO-DIMENSIONAL FLOW OF LIKE-SIGN VORTICES"

Physics of Fluids, Vol. A 5, 1993, pp. 2484-2501.

The Hamiltonian flow of a set of point vortices of like sign and strength has a low-temperature phase consisting of a rotating triangular lattice of vortices, and a normal temperature turbulent phase of random clusters of vorticity that orbit about a common center along random tracks. The mean-field flow in the normal temperature phase has similarities with turbulent quasi-two-dimensional rotating laboratory and geophysical flows, whereas the low-temperature phase displays effects associated with quantum fluids. In the normal temperature phase, the vortices follow power law clustering distributions, while in the time domain random interval modulation of the vortex orbit radii fluctuations produces singular fractional exponent power-law low-frequency spectra corresponding to time autocorrelation functions with fractional exponent power-law tails. Enhanced diffusion is present in the turbulent state, whereas in the solid-body rotation state vortices thermally diffuse across the lattice. Over the entire temperature range the interaction energy of a single vortex in the field of the rest of the vortices follows positive temperature Fermi-Dirac statistics, with the zero-temperature limit corresponding to a Maxwellian distribution. Analyses of weather records dependent on the large-scale quasi-two-dimensional atmospheric circulation suggest the presence of singular fractional exponent power-law spectra and fractional exponent power-law autocorrelation tails, consistent with the theory.

Viieru, D., Albertani, R., Shyy, W. and Ifju, P. G.

"EFFECT OF TIP VORTEX ON WING AERODYNAMICS OF MICRO AIR VEHICLES"

AIAA Paper No. 2004-4971, Providence, RI, August 2004

Tip vortex induces downwash movement that reduces the effective angle of attack. When a wing has a relatively low aspect ratio, such as that employed by the micro air vehicle (MAV), the induced drag by the tip vortex is relatively large and therefore the aerodynamic performance of the vehicle are deteriorated. In this paper we study the effect of two MAV wing shapes, a baseline wing and a modified one, on the overall aerodynamic performances. Also, an endplate is attached to the modified wing to help probe the tip vortex effects. The investigation is facilitated by solving the Navier-Stokes equations around a rigid wing with a root chord Reynolds number of $9 \times 10,000$. It is confirmed that with modest angle of attack, the modified wing with endplate can improve the lift-to-drag ratio by reducing the drag. However, as the angle of attack becomes higher, the wing tip vortex is stronger and the endplate effect decreases.

Viieru, D., Albertani, R., Shyy, W. and Ifju, P. G.

"EFFECT OF TIP VORTEX ON WING AERODYNAMICS OF MICRO AIR VEHICLES"

Journal of Aircraft, Vol. 42, No. 6, Nov.-Dec. 2005, pp. 1530-1536

Tip vortex induces downwash movement, which reduces the effective angle of attack of a wing. For a low-aspect-ratio, low-Reynolds-number wing, such as that employed by the micro air vehicle (MAV), the induced drag by the tip vortex substantially affects its aerodynamic performance. In this paper we use the endplate concept to help probe the tip-vortex effects on the MAV aerodynamic characteristics. The investigation is facilitated by solving the Navier-Stokes equations around a rigid wing with a root-chord Reynolds number of 90,000. It is confirmed that with modest angles of attack the endplate can improve the lift-to-drag ratio by reducing the drag. However, as the angle of attack becomes substantial, the wing tip vortex is stronger and the endplate loses its effectiveness. Detailed fluid flow structures are presented to offer insight into the physics responsible for the observed phenomena.

Vijgen, P. M. H. W., vanDam, C. P. and Holmes, B. J.

"SHEARED WING-TIP AERODYNAMICS: WIND-TUNNEL AND COMPUTATIONAL INVESTIGATION"

Journal of Aircraft, Vol. 26, No. 3, March 1989, pp. 207-213.

Computational and experimental performance benefits are presented for a high-aspect-ratio unswept wing configuration with sheared tips. The sheared tip is a highly swept and highly tapered surface located in the same plane as the inboard wing panel to which it is attached. The computational results were obtained with an inviscid surface panel method that models the nonlinear influence of the trailing wake. Both wind-tunnel and calculated results were obtained for a 12-ft span wing model with various wing-tip configurations. The computational and experimental data are in fair agreement and demonstrate that sheared wing tips can reduce induced drag at cruise and climb lift coefficients. The

drag reduction is the result of wake deformation effects and changes in spanwise load distribution. Wind-tunnel measured longitudinal and lateral directional stability characteristics are also presented for the various wing-tip layouts.

Villardaga, S., Serrano, D., Bas, I., Roig, J. and Batlle, J.

"ADVANCED AUTOMATION IN AIR TRAFFIC SIMULATION FOR ATM DISTURBANCES ASSESSMENT"

Application and Theory of Automation in Command and Control Systems (ATACCS) 2011, May 2011, Barcelona, Spain.

In the context of an ever-increasing complexity in ATM, there is a need for mechanisms to automatically assess new procedures and concepts and their impact into global and specific airspace. To this purpose, this study describes the development of a complex system (system of systems): a simulated Air Traffic environment to analyze the effect of Wake Vortices to trailing aircraft in different flight phases. This project is part of AVANT: a project part-funded by the European Regional Development Fund (ERDF) under the Regional Competitiveness and Employment.

Visser, K. D. and Nelson, R. C.

"MEASUREMENTS OF CIRCULATION AND VORTICITY IN THE LEADING-EDGE VORTEX OF A DELTA WING"

AIAA Journal, Vol. 31, No. 1, January 1993, pp. 104-111.

Cross-wire measurements of the flowfield above a 75-deg flat plate delta wing were performed at a centerline chord Reynolds number of 250000. Surveys normal to the planform yielded velocity field data at incidence angles of 20 and 30 deg for a series of chordwise locations. The distribution of the velocity, axial velocity, and circulation showed a strong conical behavior upstream of the breakdown region and away from the apex and trailing edge regions. Spanwise velocity and vorticity profiles through the core of the vortex upstream of breakdown were scaled with the local geometry. Prior to breakdown, most of the axial vorticity in the primary vortex was observed to be concentrated at the center of the vortex, in a region of about twice that of the subcore diameter. The influences of changes in the angle of attack on axial vorticity with the opposite sense, such as that found in the secondary vortex, was much less than the vorticity in the primary vortex. The growth of the vortex circulation with distance from the apex was approximately linear over the forward end of the planform. The rate of growth was observed to decrease, however, aft of the midchord location. Radial circulation distributions scaled with the local semispan and exhibited a logarithmic behavior with increasing distance from the subcore, implying the possibility of a strong dependence on the local Reynolds stresses. Finally, parameters derived from slender body theory are shown to correlate the circulation for wings of different sweep.

Visser, K. D., Nelson, R. C. and Ng, T. T.

"METHOD OF COLD SMOKE GENERATION FOR VORTEX CORE TAGGING"

J. Aircraft, Vol. 25, No. 11, November 1988, pp. 1069-1071

The use of smoke or dye to enhance a moving fluid visually is an invaluable aid in gaining a better understanding of intricate flow motions. Not only can complex flows, such as those of a three-dimensional nature, be visualized, but the global views provided by the markers can help point out important flow regions where quantitative data should be taken. A particularly interesting flow visualization problem concerns the so-called dark-core region of the vortices formed on the upper side of a delta wing. Smoke visualization techniques employing upstream injection of vaporized kerosene have failed to entrain any smoke particles into the core region. The core is seen as a dark region along the axis of the vortices void of any particles. Other flow visualization experiments using particles introduced into a vortical flowfield confirm the absence of smoke in the core.

Vitalle, R. F.

"AN ANALYSIS OF EN ROUTE WAKE TURBULENCE BEHAVIOR BASED ON IN-FLIGHT MEASUREMENTS"

Air Traffic Control Association (ATCA) Annual Conference, October 2017, Gaylord, MD.

The recent incident involving the encounter of an Airbus A380 wake vortex by a Challenger 604 has drawn attention to the potential hazard of wake vortices en route. To broaden the understanding of the risks associated with en route vortex systems, the FAA in collaboration with the National Research Council of Canada (NRC) has collected high altitude wake turbulence data. An analysis of wake vortex fields based on such in-flight measurements has shown that wake turbulence may exist at distances well beyond minimum separation. The strength of these vortices, as well as transport and decay rates, was found to be highly dependent on atmospheric conditions. A study of historical weather data provided herein suggests that the likelihood for atmospheric conditions that trigger a wake encounter increases as longitudinal separations are reduced. Implementing wake mitigation strategies may allow increasing NAS capacity without compromising safety. Along track separation increases, altitude changes or lateral offsets are discussed as potential mitigations that may be useful in avoiding wake turbulence.

Vitalle, R. F. and Davenport, L. H.

"A METHODOLOGY FOR THE IDENTIFICATION AND MAPPING OF HIGH ALTITUDE AIRCRAFT WAKE VORTICES"

AIAA Paper 2017-4239, June 2017, Denver, CO.

The investigation of the behavior and characteristics of aircraft wake turbulence at high altitude is an important step in defining the risks involved when developing new procedures, separation standards, and mitigation techniques. In this work, high altitude aircraft wake turbulence data has been collected through direct measurement of atmospheric parameters. A retrofitted CT-133 performed wake vortex interceptions in trail of commercial transport category aircraft. A methodology is presented to evaluate the characteristics and behavior of wake vortices through analysis of measured winds in the wake turbulence area associated with the location of the condensate trails. The methodologies described in

this research seek to increase understanding of the behavior of wake turbulence data generated by the current suite of wake behavior models for aircraft operating enroute at high altitudes.

Vladimirova, N. A. and Sakovich, V. S.

"VORTEX FLOW SIMULATION IN THE FRAMEWORK OF A BOUNDARY-VALUE PROBLEM FOR THE EULER EQUATIONS"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 43-55

For modeling three-dimensional vortex structures forming the vortex wake behind the wing of an aircraft, numerical integration of the full system of the Euler equations is carried out by means of a time iterations method to obtain the steady-state solution using multigrid technology. A numerical algorithm for describing such vortex flows takes into consideration flow compressibility, the free-stream velocity is assumed subsonic, the influence of viscosity is ignored. Discretization of the Euler equations is performed in the context of a finite volume method, structured C-H computational grids are used, for time integration an explicit scheme is employed. Two boundary-value problems are considered: interaction of a wing vortex wake with a solid boundary and diffraction of a vortex (or a vortex pair) by a solid surface (by a wing). The first problem deals with modeling of the effects of ground proximity on the flow around a swept wing and the structure of the near wake behind it. The second problem is concerned with schematizing the interaction of a lifting wing and its vortex system with the vortex wake generated by a heavy aircraft (the case of the longitudinal diffraction of the vortices by the wing). For initializing and describing mathematically the velocity field in the far wake an empirical model is employed.

Vladimirova, N. A., Vyshinsky, V. V., Kravchenko, S. A. and Sakovich, V. S.

"INVESTIGATION INTO VORTEX STRUCTURES IN THE FRAMEWORK OF A BOUNDARY-VALUE PROBLEM FOR THE EULER EQUATIONS"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 66-80

In the framework of the 3-D time-dependent Euler equations, the formation of the vortex system about a wing-body configuration and individual fragments of the vortex structure evolution in the far field in the presence of the vertical plane of symmetry and in-ground effect are considered. Basic outcome of the work is in determining the area of applicability of Jameson's numerical scheme to solve this boundary-value problem when studying the formation and development of a vortex wake. [In Russian.

Voevodin, A. V.

"NUMERICAL INVESTIGATION OF THE EFFECTS OF WINGLETS ON THE EVOLUTION OF AN AIRCRAFT VORTEX WAKE"

Fluid Dynamics, Vol. 43, No. 5, 2008, pp. 725-730.

The effect of winglets on the aerodynamic characteristics of a heavy aircraft and the parameters of the vortex wake behind it is investigated for the landing regime. The solution of the complete problem is obtained by breaking up the wake into three regions, namely, the near, intermediate, and far flowfields, in which the corresponding subproblems are successively solved. The wake flowfields are obtained at different distances from the aircraft, together with the distributions of the mean azimuthal velocity over the vortex radius, and the lifetime of the vortex system is estimated for several one- and two-element wingtip versions. All the results are compared with those for the baseline layout with no winglets.

Vogel, C. M. and Devenport, W. J.

"THE SOURCE AND EVOLUTION OF TURBULENCE IN TRAILING VORTEX PAIRS"

VPI-AOE-217, April 1995, Virginia Polytechnic Inst. and State Univ., Blacksburg, VA.

The reanalysis of data obtained from the experimental studies of two different trailing vortex pairs has been conducted to obtain a more complete understanding of the turbulence structure of these flows. Statistical and spectral results, as well as filtered results and estimates of the effects of vortex wandering on the characteristics of the flows are presented. The results of the vortex pair are compared with the data from the experimental study of an isolated vortex conducted under similar testing conditions and model configuration to distinguish between the structure and effects of the separate vortices from those of vortex interaction. The analysis of a counter-rotating vortex pair reveals that initially the vortices develop in a manner like an isolated vortex. The cores appear laminar and the turbulence structure outside them is dominated by the spiral wakes. After some distance, flow inside and outside the cores becomes much more turbulent. The cores begin to grow and decay. The results indicate that this change may be a result of wave instabilities developed in the cores. The analysis of the co-rotating vortex pair reveals that turbulence is present in the cores as they spiral about each other and move downstream. After a certain distance, the cores merge into a single core, which contains more turbulence and is over twice the size of the pair that created it. As merger comes to completion, a symmetric core is formed which has much less turbulence. Merger appears to cause an increased rate of vortex decay.

Vogt, A., Baumann, P., Gharib, M. and Kompenhans, J.

"INVESTIGATIONS OF WING TIP VORTEX IN AIR BY MEANS OF DPIV"

AIAA Paper No. 1996-2254, New Orleans, LA, June 1996

This paper presents results of Particle Image Velocimetry measurements on the tip vortex of a NACA0012 wing. These results were achieved utilizing a digital recording technique based on a

modified CCD video camera and an evaluation process which is based on the cross-correlation technique. Instantaneous velocity fields showing the complete vortex could be gained. Because for each set of experiment parameters many PIV images were recorded, and because the evaluation was fully automatic, time averaging of several hundred images was also possible. Locating the vortex core in each measured velocity field for a fixed free stream velocity allowed to determine the trajectory of the vortex core with respect to the angle of attack. Due to the higher spatial resolution of PIV images taken with a smaller field of view it was also possible to determine the azimuthal velocity components along a line through the vortex core. These velocity profiles indicate a nonlinear increase of the azimuthal velocity with growing distance from the vortex center as it is implied by the solid body rotation model of the vortex core.

Voigt, C., Jurkat, T., Schlager, H., Schauble, D., Petzold, A. and Schumann, U.

"AIRCRAFT EMISSIONS AT CRUISE AND PLUME PROCESSES"

In: Atmospheric Physics, Research Topics in Aerospace, U. Schumann (editor), Springer-Verlag Berlin Heidelberg, 2012, pp. 675-692..

The detection of aircraft emissions at cruise altitudes helps to understand and assess the effects of aviation on atmospheric composition and climate. Since the early 1990s, aircraft emissions of carbon dioxide, water vapor, nitrogen and sulfur oxides, aerosol and soot and their processing in the atmosphere as well as contrail formation have been measured in situ with the instrumented DLR research aircraft Falcon. Scientific results from a series of aircraft missions are summarized and explained, uncertainties are discussed and suggestions are made on how to move forward.

Vollmer, L., Steinfeld, G., Heinemann, D. and Kuhn, M.

"ESTIMATING THE WAKE DEFLECTION DOWNSTREAM OF A WIND TURBINE IN DIFFERENT ATMOSPHERIC STABILITIES: AN LES STUDY"

Wind Energy Science, Vol. 1, September 2016, pp. 129-141.

An intentional yaw misalignment of wind turbines is currently discussed as one possibility to increase the overall energy yield of wind farms. The idea behind this control is to decrease wake losses of downstream turbines by altering the wake trajectory of the controlled upwind turbines. For an application of such an operational control, precise knowledge about the inflow wind conditions, the magnitude of wake deflection by a yawed turbine and the propagation of the wake is crucial. The dependency of the wake deflection on the ambient wind conditions as well as the uncertainty of its trajectory are not sufficiently covered in current wind farm control models. In this study we analyze multiple sources that contribute to the uncertainty of the estimation of the wake deflection downstream of yawed wind turbines in different ambient wind conditions. We find that the wake shapes and the magnitude of deflection differ in the three evaluated atmospheric boundary layers of neutral, stable and unstable thermal stability. Uncertainty in the wake deflection estimation increases for smaller temporal averaging intervals. We also consider the choice of the method to define the

wake center as a source of uncertainty as it modifies the result. The variance of the wake deflection estimation increases with decreasing atmospheric stability. Control of the wake position in a highly convective environment is therefore not recommended.

Vollmers, H.

"DETECTION OF VORTICES AND QUANTITATIVE EVALUATION OF THEIR MAIN PARAMETERS FROM EXPERIMENTAL VELOCITY DATA"

Measurement Science and Technology, Vol. 12, 2001, pp. 1199-1207.

Efficient and well adapted algorithms are necessary to analyze the large number of vector fields generated when observing time dependent flow fields. This paper discusses several possibilities of vortex detection and characterization from two-dimensional instantaneous vector fields like those obtained by means of particle image velocimetry (PIV) technique.

von Karman, T. and Tsien, H-S.

"LIFTING-LINE THEORY FOR A WING IN NON-UNIFORM FLOW"

Quarterly of Applied Mathematics, Vol. 3, No. 1, April 1945, pp. 1-11.

The lifting line theory developed by Prandtl has been extended to handle non-uniform incoming flow. A general and more satisfactory solution for the flow of a wing in a non-uniform stream is examined as a generalized case, introducing the modifications of Prandtl's fundamental concepts. The resulting formulations included generalized expressions of the downwash and induced drag.

Vorropoulos, G.

"AN EXPERIMENTAL STUDY OF COMPRESSIBILITY EFFECTS IN THE LEADING EDGE VORTEX OF A DELTA WING AT INCIDENCE USING LASER DOPPLER VELOCIMETRY"

PhD Thesis, June 1983, Universite Libre de Bruxelles, Rhode-Saint-Genese, Belgium.

The purpose of the work reported in this thesis is the investigation of compressibility effects on a delta wing leading edge vortex by measuring the distributions of the axial and circumferential velocity components across it. These measurements were performed by making use of Laser Doppler Velocimetry (LDV) since this technique does not perturb the vortical flow field. Due to the severe problems arising in LDV applications in compressible vortices, all components at the LDV system used in this study were optimized. Furthermore, the problems of directional bias and seeding particles behavior in high-speed vortices were solved analytically for the first time to improve the accuracy and validity of the results. The LDV system was successfully used up to $M_{\infty} = 0.80$. The LDV measurements were supported by flow visualizations (including the use of a new type of schlieren system specially developed for the purposes of this investigation). The velocity measurements have shown a drastic modification of the vortex structure as a result of compressibility: instead of an axial

velocity excess (as observed at low speed investigations) an axial velocity deficit was observed at $M_{\infty} \geq 0.60$. Furthermore, a pronounced asymmetry became evident from these measurements. The possibility of the existence of a shock wave was examined but neither the LDV measurements, nor the flow visualizations provided concrete evidence of its existence. Since the already existing theory on the compressible vortex structure (based among other assumptions on the vortex axisymmetry) is not adequate to predict the observed compressibility phenomena, detailed theoretical investigation of the compressible vortex is clearly needed in the future.

Voss, G.

"WAKE VORTEX ALLEVIATION BY DIFFERENTIAL AND OSCILLATING FLAP SETTING: AN EXPERIMENTAL STUDY"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

One approach to bring a wake vortex to an early decay is the application of configurative methods to the lift devices. That means for example the trigger of vortex instabilities with movable wing devices like DLC flaps etc. One example of a principal model which was provided at DLR by Vollmers et al. should be shown that it is possible to excite long wavelength instabilities whereas the attention is turned to Crow instabilities. The principal model generates in this connection by means of rectangular wing and a smaller HTP a counter-rotating 4-vortex system. In former studies it was shown that counter-rotating 4-vortex systems are a capable investigation object. On both sides of the model wing respectively three trailing edge flaps are mounted which can be independently moved. Selected oscillating motion causes the periodic generation and collapse of small vortices which are coming to an interaction with the main vortices. In this presentation the results of experimental investigations will be presented.

Voss, G., Carmer, C. V., Konrath, R., Stumpf, E., Kruckeberg, C.-P., Meyer, H. and Mattner, H.

"WAKE VORTEX ALLEVIATION BY DIFFERENTIAL AND OSCILLATING FLAP SETTING: A COMPARATIVE NUMERICAL AND EXPERIMENTAL STUDY"

1st CEAS European Air and Space Conference, Berlin, Germany, CEAS-2007-006, September 2007, pp. 1007-1016

In this article the results of numerical calculations and experimental studies on wake vortex alleviation using Differential Flap Setting (DFS) and Oscillating Flap Setting (OFS) by means of a principal model with rectangular wing as a vortex generator should be presented. The numerical part of the examination was made as a Euler-computation provided with flow solver TAU, the experiment was performed in a water towing tank at DLR Gottingen. The comparison of different configurations according to flap setting, trigger frequency and influence of HTP vortex was conducted in this paper. Both numerical and experimental investigations have shown that it is possible to affect the wake vortex

development using configurative methods on lift devices. Further investigations have to be done to calculate the circulation and the rolling moment influence on following aircraft.

Voss, G., Gerz, T., Baumann, R., Stumpf, E. and Press, M.

"WAKE VORTEX ALLEVIATION BY DIFFERENTIAL FLAP SETTING AND OSCILLATING FLAP SETTING: A FLIGHT TEST"

AIAA Paper No. 2009-3947, June 2009, San Antonio, TX.

This article presents two methods for early vortex decay experimentally investigated by flight testing. The first item is the Differential Flap Setting (DFS). Here, small changes in configuration of lift devices are applied, which leads to a variation of spanwise lift distribution. This generates a selected multiple-vortex-system, whose vortices interact one another and contribute to decay the dangerous main vortices. The second method is the Oscillating Flap Setting (OFS). Aim of this is the trigger of vortex instabilities by periodic moving of aileron and special additional flaps. Every vortex in a vortex system has a characteristic frequency. If this frequency is triggered, resonance occurs which may lead to a vortex decay. Usually, the decay is caused by atmospheric disturbances namely side wind, shear wind or thermal wind. It is possible to accelerate this process by selected triggering of these instabilities. In the flight test described in this article exclusively the behavior of vortices with triggering of long-wavelength instabilities (e.g. Crow-instability) was observed and measured.

Voss, G., Melber-Wilkending, S. and Rudnik, R.

"PREMATURE DECAY OF WAKE VORTICES WITH DIFFERENTIAL- AND OSCILLATING FLAP SETTING"

European Conference on Computational Fluid Dynamics, ECOMAS CFD 2006, 2006, TU Delft, The Netherlands.

This paper gives an overview of the research on wake vortex decay using Differential Flap Setting (DFS) and Oscillating Flap Setting (OFS). The concept of DFS deals with the small deflection of flaps and elevator to produce additional vortices which interact with the vortices from wing, elevator, flaps, and wing-body-junction. Numerical calculations with the A340-300 model at this topic are presented in the first part of the paper. On the other hand, the OFS concept works with the periodic movement of DLC (direct lift control) flaps and/or ailerons to trigger inherent instabilities of the vortices. The basic mechanism of the introduction of the periodic disturbance into the flow field is a periodic alteration of the spanwise lift distribution, i.e. of the circulation and spacing ratios of the distinct vortex pairs in the extended wake vortex flowfield. This can be achieved both by pitch oscillation and oscillating DLC flaps. Pitch oscillation alone are sufficient for accelerating Crow instability as proven already in the 1970s with small aircraft. One can distinguish between long-wavelength and short-wavelength instabilities. The second part of this paper is truncated on short-wavelength instability examinations i.e. the Crow instability.

Voutsinas, S. G.

"VORTEX METHODS IN AERONAUTICS: HOW TO MAKE THINGS WORK"

International Journal of Computational Fluid Dynamics, Vol. 20, No. 1, January 2006, pp. 3-18

Vortex methods constitute a particular class in CFD. They are grid-free, use Lagrangian co-ordinates and most importantly they use vorticity as main flow variable instead of the velocity. In aeronautics they have been in use for over than 30 years with impressive results. However, rather a limited number of researchers would prefer them. This could be due to some particularities vortex methods have in their implementation. In view of trying to clarify things, this paper reviews the current state of the subject and details some of the 'difficult' points of vortex methods. Although the focus is mainly on rotor problems, the presented techniques can be used in other applications as well.

Voyevodin, A. V., Gaifullin, A. M., Zakharov, S. B. and Sudakov, G. G.

"A ZONAL METHOD FOR COMPUTING THE VORTEX WAKE BEHIND AN AIRCRAFT"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 54-65

Based on an analysis of reported experimental data and theoretical models, an empirical model of the aircraft wake has been constructed. The model is considered as an initial approximation while creating a theoretical vortex wake model. Using the asymptotic analysis of the phenomena and numerical solutions to the problems inherent zones and numerically matching the solutions at zone boundaries, a four-zone model was constructed that refines the empirical model and does not lean upon empirical relationships. Such a strategy enables further developing the model with retaining its usefulness as the mathematical tools and numerical methods upgrade. [In Russian.]

Vrancken, P. S.

"AIRBORNE REMOTE DETECTION OF TURBULENCE WITH FORWARD-POINTING LIDAR"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 22, 2016, Springer International Publishing Switzerland, pp. 443-464.

Presently, the airborne remote detection of atmospheric turbulence is limited to radar-visible regions of the sky, i.e., zones that contain hydrometeors like rain or cloud droplets. The bulk of the actual turbulence, possible in clear air at all flight altitudes, evades such a remote detection, though a remote determination of aircraft-relevant physical parameters relevant to turbulence could significantly increase flight safety. The following chapter reviews possible techniques of remote turbulence detection in clear air and identifies the most promising approaches for future aircraft. These are shown to be optical methods, i.e., LIDAR (Light Detection and Ranging) systems. Principles, as well as pros and cons of some complementary lidar techniques, are discussed.

Vyazmina, E., Nichols, J. W., Chomaz, J.-M. and Schmid, P. J.

"BIFURCATION STRUCTURE OF VISCOUS VORTEX BREAKDOWN"

AIAA Paper 2008-3797, June 2008, Seattle, WA

Incompressible axisymmetric swirling flow with open boundaries is studied by means of direct numerical simulation (DNS). The effects of viscosity and external axial pressure gradient near critical swirl number are investigated. The solution branches obtained from DNS match the bifurcation diagrams from previous theoretical and numerical studies and extend their results.

Vyshinsky, V. V.

"FLIGHT SAFETY, AIRCRAFT VORTEX WAKE AND CRISIS OF AIRPORTS"

In: Investigation of Vortex Wake Evolution and Flight Safety Problems - Collection of Papers, Trudy TsAGI, Vol. 2627, Publishing Dept. of TsAGI, Moscow, Russia, 1997, pp. 5-2.

The paper deals with restrictions on airport capacity associated with the potential hazard for an aircraft in takeoff or landing to encounter the vortex wake generated by another aircraft. The complexity of the problem under study and the lack of a single research tool make one employ a 'mosaic' approach based on combined use of various methods. A specific difficulty therewith appears of the asymptotically non-rigorous division of the problem into subproblems and of thoroughly matching the results obtained. The goal of this work is to validate and assess the potentialities of the methods used and to reveal their weaknesses and strengths as well as to discuss the results obtained. The basic guideline in assessing the methods is the possibilities for obtaining concrete technical decisions aimed at resolving contradictions related to the impossibility of realizing the required air traffic growth in the near future in the framework of available technologies.

Vyshinsky, V. V.

"INVESTIGATION OF THE AIRCRAFT VORTEX WAKE EVOLUTION AND FLIGHT SAFETY"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 5-21

Investigated in the present report are the problems of decreasing separation distances between aircraft during their takeoffs and landings. This work reflects in a condensed form the efforts of a large team of specialists and presents a general view on the problem under study, whose complexity lies basically in the fundamental impossibility to create a single method and universal tool of investigation. A fragmentary approach is used with asymptotically non-strict splitting of the problem into subdomains and a multiple mosaic selection of research tools. [In Russian.

Vyshinsky, V. V.

"FLIGHT SAFETY, AIRCRAFT VORTEX WAKE AND AIRPORT OPERATIONAL CAPACITY"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 7-2.

In the framework of the multidisciplinary approach, the vortex wake generated by a heavy passenger aircraft in takeoff and landing regimes is studied and practical ways to enhance the airport capacity are sought. The problem falls into several integral parts: atmospheric turbulence, aircraft generating the multiple vortex structure, coherent vortex pair under atmospheric turbulence environment, aerodynamics, and flight dynamics of a trailing aircraft under wake turbulence conditions. The author gives also a substantiation of the Project's structure and an appraisal of the results obtained and the prospects of separate research directions and considers a matrix of both possible and solved problems.

Vyshinsky, V. V.

"AIRCRAFT VORTEX WAKES AND AIRPORT CAPACITY"

SAE Paper 975519 (also, AIAA Paper 97-5519), Anaheim, CA, October 1997

The paper deals with restrictions on airport capacity associated with the potential hazard for an aircraft in takeoff or landing to encounter the vortex wake generated by another aircraft. The complexity of the problem under study and the lack of a single research tool make one employ a 'mosaic' approach based on combined use of various methods. A specific difficulty therewith appears of asymptotically non-rigorous division of the problem into subproblems and of thoroughly matching the results obtained. The goal of this work is to validate and assess the potentialities of the methods used and to reveal their weaknesses and strengths as well as to discuss the results obtained.

Vyshinsky, V. V.

"FLIGHT SAFETY, AIRCRAFT VORTEX WAKE AND AIRPORT OPERATION CAPACITY"

Air and Space Europe, Vol. 3, No. 3-4, 2001, pp. 206-20.

Atmospheric vortices are very stable formations featuring a slow mass, momentum, and energy exchange with surrounding atmosphere, they are rather difficult for understanding. Concrete measures, concrete technical decisions can be suggested for improving flight safety in the wake turbulence environment and airport operational capacity. Wake vortex investigation is the example of the fruitful international cooperation. A unique experience gained over the last six years of continuous researches requires that it be practically embodied in the technical decisions usable for world community.

Vyshinsky, V. V.

"AIRCRAFT VORTEX WAKE, FLIGHT SAFETY AND CRISIS OF AIRPORTS"

ICAS Paper 98-6.5.1, Sept. 1998, Melbourne, Australia.

In the framework of computational and experimental methods, the problem is solved on improving airport capacity. For this purpose a two-level aerodynamic wake model was developed as well as models intended for studying the problems of flight dynamics, structural strength and aeroelasticity. The element of stochasticity inherent in the phenomenon under study is incorporated into the combined model through the two last models. The mathematical models are combined into a single structure, which enables their using to assess hazardous situations associated with vortex wake encounters of aircraft, to construct criteria to judge as reliably as possible the severity of the vortex hazard in landing, to determine the relationship between the probability of accidents and main parameters of both landing and following aircraft, weather conditions in the airport area and distances between aircraft, to work out recommendations on timely detection of vortex wakes and pilot actions to execute a vortex avoidance maneuver and on establishing safe-separation standards.

Vyshinsky, V. V. and Kuznetsov, O. A.

"WAKE VORTEX PROBLEMS FOR THE AIRPORT WITH CROSSING RUNWAYS"

EUROMECH Colloquium No. 433, Dynamics of Trailing Vortices, Aachen, Germany, March 2002

Critical from the standpoint of structural strength are wake encounters at angles close to 90 degrees, which is highly probable in airport airspace, especially when airports have crossing runways. In this case a passage through the most dynamic portion of the vortex gust takes about one second, so that one can expect abrupt changes in external forces. They can excite aeroelastic oscillations of the airframe and, consequently, dynamic loads. Since in the course of time the strength of vortices decreases, the response to the wing root bending moment also weakens: the greater is the atmospheric turbulence intensity the greater is the rate of loads' diminishing. The panel method is used to calculate the flow about the aircraft and the vortex wake shape behind it. These data are used as the initial ones for computing the vortex wake evolution in the near field up to the vortex merging (2D RANS with a specially developed algebraic eddy viscosity model). For simulating the vortex wake evolution in the turbulent atmospheric boundary layer, a package of CFD codes GROUNDWAKE was created.

Vyshinsky, V. V. and Soudakov, G. G.

"INVESTIGATION OF THE VORTEX WAKE EVOLUTION AND FLIGHT SAFETY"

ICAS 1996, September 1996, Sorrento, Napoli, Italy.

Investigated in the present report are the problems of decreasing separation distances between aircraft during their takeoffs and landings. This work reflects in a condensed form the efforts of a large collective of scientists and presents a general view on the problem under study, whose complexity lies mainly in the fundamental impossibility to create a single method and universal tool of investigation.

The authors use a fragmentary approach with asymptotically non-strict splitting of the problem into subregions and a multiple mosaic selection of separate subproblems, in the strict sense improperly posed for solving main problem.

Vyshinsky, V. V. and Yaroshevsky, V. A.

"VORTEX WAKE SAFETY: AERODYNAMICS AND FLIGHT DYNAMICS ASPECTS OF THE PROBLEM"

AIAA Paper No. 1998-2522, Albuquerque, NM, June 1998

The main problem of the paper is an approach to establishing criteria for aircraft safe separation distances during takeoff and landing operations on the same runway. The vortex wake longitudinal penetration is a critical situation here. A 'worst case' method is not acceptable in this case; instead of it the probabilistic approaches are used.

Wachspetess, D. A., Quackenbush, T. R. and Boschitsch, A. H.

"FIRST-PRINCIPLES FREE-VORTEX WAKE ANALYSIS FOR HELICOPTERS AND TILTROTORS"

American Helicopter Society 59th Annual Forum, May 2003, Phoenix, AZ.

The development of high-fidelity models of the rotor wake is an issue of continuing, critical importance in the design of new helicopters and tiltrotors, as well as in the understanding of a wide range of problems in rotor aerodynamics, dynamics, and acoustics. This paper outlines a set of interrelated modeling methods developed over the last two decades that have yielded a unified free wake model suitable for the full range of current helicopter and tiltrotor designs. These methods, now embedded in the CHARM comprehensive analysis of rotorcraft aeromechanics, can produce high fidelity predictions of rotor performance, unsteady airloads, and noise as well as accurate predictions of rotor-induced flow fields and airframe loads over a wide range of aircraft configurations. An important feature of the wake modeling described here is that it is a first-principles analysis completely free of user-selected empirical parameters. This allows the model to be used as a design tool for analyzing future rotorcraft concepts as well as in flight simulations where wake characteristics vary with the flight condition. This paper describes the key technical elements of this model and provides numerous examples of its validation against challenging data sets for a wide range of rotorcraft applications. Results include new correlations with Tilt Rotor Aeroacoustics Model airloads measurements establishing that both helicopter and tiltrotor aeromechanics phenomena can be predicted accurately without adjusting the wake model.

Waco, D. E.

"VARIATION OF TURBULENCE WITH ALTITUDE TO 70,000 FT"

Journal of Aircraft, Vol. 13, No. 12, December 1976, pp. 981-986.

The ratio of turbulent to total flight miles has been determined for altitudes up to 65,000 ft by comparing various turbulence data collection programs (e.g., ALLCAT, NASA, NATO, RAE, etc.). An evaluation was made of the criteria used to distinguish turbulence from smooth flight. Results can be used to update currently accepted models of turbulence variation with altitude. The percentage of flight miles with turbulence was found to be near 5% for the entire altitude range between 15,000 and 40,000 ft. Turbulence frequency increased below 15,000 ft, gradually down to 10,000 ft but markedly below 5,000 ft, and decreased above 40,000 ft, dropping to 1% near 65,000 ft. Terrain roughness had a pronounced effect on increasing both amount and intensity of turbulence at all altitudes. At low altitudes (below 1,000 ft) moderate or greater turbulence was up to 13 times more frequent over high mountains than over flat terrain and at least 3 times more frequent above 45,000 ft. The frequency of turbulence was re-evaluated for the HICAT program by careful examination of true gust velocity time histories. The ratio of turbulent to total flight miles was only 70% of the value previously arrived at in the HICAT program (only 33% for moderate and greater turbulence) when 'smooth' and low-intensity portions of the turbulent encounters were properly identified.

Wadcock, A. J., Ewing, L. A., Solis, E., Potsdam, M. and Rajagopalan, G.

"ROTORCRAFT DOWNWASH FLOW FIELD STUDY TO UNDERSTAND THE AERODYNAMICS OF HELICOPTER BROWNOUT"

American Helicopter Society Southwest Region Technical Specialists' Meeting, Technologies for the Next Generation of Vertical Lift Aircraft, October 2008, Dallas-Fort Worth, TX.

Rotorcraft brownout is caused by the entrainment of dust and sand particles in helicopter downwash, resulting in reduced pilot visibility during low, slow flight and landing. Recently, brownout has become a high-priority problem for military operations because of the risk to both pilot and equipment. Mitigation of this problem has focused on flight controls and landing maneuvers, but current knowledge and experimental data describing the aerodynamic contribution to brownout are limited. This paper focuses on downwash characteristics of a UH-60 Blackhawk as they pertain to particle entrainment and brownout. Results of a full-scale tuft test are presented and used to validate a high-fidelity Navier-Stokes computational fluid dynamics (CFD) calculation. CFD analysis for an EH-101 Merlin helicopter is also presented, and its flow field characteristics are compared with those of the UH-60.

Wadcock, A. J., Yamauchi, G. K., Heineck, J. T., Silva, M. J. and Long, K. R.

"PIV MEASUREMENTS OF THE WAKE OF A TANDEM-ROTOR HELICOPTER IN PROXIMITY TO A SHIP"

Proc. American Helicopter Society 4th Decennial Specialists' Conf. on Aeromechanics, Jan. 2004, San Francisco, CA.

The aerodynamic interaction between a tandem-rotor helicopter and an amphibious assault ship is described. The investigation used 1/48th-scale helicopter and ship models. The test was conducted in the Army 7- by 10-ft wind tunnel at NASA Ames Research Center. Particle Image Velocimetry was used

to acquire 3-component velocity field measurements of the ship air-wake and the combined wake of the tandem-rotor helicopter and ship. Ship-alone air-wake measurements are presented for yaw angles of 0, 5, 10 and 15 degrees, for a wind speed of 22.5 ft/sec at one aircraft landing spot of primary interest. The combined wake of the tandem-rotor helicopter and the ship air-wake are described in considerable detail at the same landing spot for both zero- and 15-degrees yaw angle. Variation of the combined wake with position of the upwind aircraft is described in detail. These measurements provide guidance in planning shipboard operations of rotorcraft.

Wadcock, A. J., Yamauchi, G. K., Solis, E. and Pete, A. E.

"PIV MEASUREMENTS IN THE WAKE OF A FULL-SCALE ROTOR IN FORWARD FLIGHT"

AIAA Paper No. 2011-3370, June 2011, Honolulu, Hawaii.

Stereo Particle Image Velocimetry (PIV) measurements were acquired in the wake of a full-scale UH-60A rotor that was tested in the National Full-Scale Aerodynamics Complex 40-ft by 80-ft Wind Tunnel. Flow field velocities were measured in a stationary cross-flow plane located at approximately 90 deg rotor azimuth. The region of interest was 4-ft high by 13-ft wide and covered the outer half of the blade radius. All measurements were acquired in forward flight conditions. The laser and camera systems were synchronized with the rotor 1/rev so that measurements were acquired for different rotor blade azimuths. The main objective of this paper is to describe the design of the PIV system and the installation of the system components in the wind tunnel. Examples of measured velocity fields are presented. These measurements represent the first PIV measurements to be made in the U.S. on a full-scale rotor in forward flight.

Wagener, T. J., Demma, N., Kmetec, J. D. and Kubo, T. S.

"2um LIDAR FOR LASER-BASED REMOTE SENSING: FLIGHT DEMONSTRATION AND APPLICATION SURVEY"

Proceedings of the 13th AIAA/IEEE Digital Avionics Systems Conference, October-November 1994, pp. 574-579

A flight test of a diode-pumped solid-state 2-um Doppler Light Detection and Ranging (LIDAR) system was conducted on-board the NASA Ames DC-8 Airborne Laboratory. This was the first ever airborne demonstration of a 2 um diode-pumped solid-state Doppler LIDAR. The LIDAR performance was verified by comparing the true-airspeed (TAS) estimate with that found using the pneumatic air data system; excellent agreement was found. The capabilities of this pulsed 2um Doppler LIDAR system include high bandwidth air data determination without the need for extensive forebody calibration, remote wind profiling as far as several kilometers away from the aircraft, eye-safe laser transmission at 2um, and diode-pumped solid-state design for compact construction and reliable performance.

Wagner, G., Jacques, D., Blake, B. and Pachter, M.

"AN ANALYTICAL STUDY OF DRAG REDUCTION IN TIGHT FORMATION FLIGHT"

AIAA Paper No. 2001-4075, Montreal, Canada, August 2001

This paper describes research in drag reduction resulting from tight formation flight. The optimal position for the wingman of a tight formation flight of T-38 Talon aircraft is determined in terms of induced drag reduction. This translates directly to fuel savings. Prime consideration is given to the effects of flying a laterally trimmed aircraft in the vortex wake of the lead aircraft. Inclusion into the analysis of the effect of the aileron deflections required for trim yields a significantly different optimal formation position when compared to previous work. Moreover, in this paper the additional benefit derived by the formation when a second wingman is added is investigated. The second wingman is shown to derive an even greater induced drag benefit than the first wingman. The analysis is performed using the vortex code, HASC95. Fuel saving benefits in the range of 11.5% for a tight three-ship formation flight of T-38s operating at Mach .54 at a 10,000-foot altitude are shown.

Wagner, S.

"ON THE NUMERICAL PREDICTION OF ROTOR WAKES USING LINEAR AND NON-LINEAR METHODS"

AIAA Paper No. 2000-0111, Reno, NV, January 2000

Flow fields around helicopter rotors are extremely complex. Thus, the solution of the governing equations can usually only be achieved by numerical methods. Different levels of approximation are used in the industrial design process. The rotor wake system must in any case be represented appropriately. Linear and non-linear methods as well as the coupling of both approaches are discussed. The linear methods are based on the solution of the Laplace equation. The corresponding integral equation is solved via boundary element methods including free wake representation. Sophistication towards non-linearity and compressibility calls for the implementation of field panel methods, where the boundary element approach is extended by using spatial distributions of non-linear source terms, thus solving the Poisson equation. Euler methods can describe transonic effects. The resulting gain in accuracy is, however, achieved at the expense of substantial increase in computational effort. Due to the complex kinematics of the system, computation of a single grid is nearly impossible. The Chimera approach provides a possible workaround procedure. The coupling of Euler and free wake panel methods is used to significantly reduce computational requirements. Special attention is devoted towards wake generation and wake capturing procedures within the aforementioned methods.

Waite, M. L. and Smolarkiewicz, P. K.

"INSTABILITY AND BREAKDOWN OF A VERTICAL VORTEX PAIR IN A STRONGLY STRATIFIED FLUID"

Journal of Fluid Mechanics, Vol. 606, 2008, pp. 239-273.

The dynamics of a counter-rotating pair of columnar vortices aligned parallel to a stable density gradient are investigated. By means of numerical simulation, we extend the linear analysis and

laboratory experiments of Billant and Chomaz (2000) to the fully nonlinear, large-Reynolds-number regime. A range of stratifications and vertical length scales is considered. At early times with a Froude number (F) less than one, linear predictions for the zigzag instability are reproduced. Short-wavelength perturbations with F greater than one are found to be unstable as well, with growth rates only slightly less than those of the zigzag instability but with very different structure. At later times, the large-Reynolds-number evolution diverges profoundly from the moderate-Reynolds-number laboratory experiments as the instabilities transition to turbulence. For the zigzag instability, this transition occurs when density perturbations generated by the vortex bending become gravitationally unstable. The resulting turbulence rapidly destroys the vortex pair.

Walden, A. B. and vanDam, C. P.

"STUDY OF THE MUTUAL INTERACTION BETWEEN A WING WAKE AND AN ENCOUNTERING AIRPLANE"

NASA/CR-1997-206493, March 1996, Univ. of California, Davis, CA

To increase airport productivity, several wind-tunnel and flight-test programs are currently underway to determine safe reductions in separation standards between aircraft. These programs are designed to study numerous concepts from the characteristics and detection of wake vortices to the wake-vortex encounter phenomenon. As part of this latter effort, computational tools are being developed and utilized as a means of modeling and verifying wake-vortex hazard encounters. The objective of this study is to assess the ability of PMARC, a low-order potential-flow panel method, to predict the forces and moments imposed on a following business-jet configuration by a vortex interaction. Other issues addressed include the investigation of several wake models and their ability to predict wake shape and trajectory, the validity of the velocity field imposed on the following configuration, modeling techniques and the effect of the high-lift system and the empennage. Comparisons with wind-tunnel data reveal that PMARC predicts the characteristics for the clean wing-body following configuration fairly well. Non-linear effects produced by the addition of the high-lift system and empennage, however, are not so well predicted.

Walden, A. B., vanDam, C. P. and Brandon, J. M.

"MODELING OF THE INTERACTION BETWEEN A LIFTING WING AND A FOLLOWING AIRCRAFT AND COMPARISON WITH EXPERIMENTAL RESULTS"

AIAA Paper No. 1996-0771, Reno, NV, January 1996

Understanding the wake-vortex/airplane interaction phenomenon is important to help define the parameters which can be used to predict a wake-vortex hazard. To understand the phenomenon, efforts are underway utilizing various computational tools as a means of modeling and verifying wake-vortex hazard encounters. The objective of this study is to assess the capability of PMARC, a low-order potential-flow panel method, to predict the forces and moments imposed on a following business-jet configuration by a wake-vortex interaction. Issues addressed include the investigation of different wake techniques and their ability to predict wake shape and trajectory, the validity of the velocity field

imposed on the following configuration and the effects of the high-lift system and the empennage on the aerodynamic characteristics of the following configuration. Comparisons with wind-tunnel data reveal that PMARC predicts the characteristics for the clean wing-body configuration fairly well. The characteristics for the complete airplane with the high-lift system deployed are not so well predicted.

Waldman, R. M. and Breuer, K. S.

"MEASUREMENT OF STREAMWISE VORTICES IN LOW-SPEED FLIGHT"

AIAA Paper No. 2012-0916, January 2012, Nashville, Tennessee.

Low Reynolds number aerodynamic experiments with flapping animals (such as bats and small birds) are of particular interest due to their application to Micro Air Vehicles which operate in a similar parameter space. Previous PIV wake measurements described the structures left by bats and birds and provided insight to the time history of their aerodynamic force generation; however, these studies have faced difficulty drawing quantitative conclusions based on said measurements. The highly three-dimensional and unsteady nature of the flows associated with flapping flight are major challenges for accurate measurements. The challenge of animal flight measurements is finding small flow features in a large field of view at high speed with limited laser energy and camera resolution. Cross-stream measurement is further complicated by the predominantly out-of-plane flow that requires thick laser sheets and short inter-frame times, which increase noise and measurement uncertainty. Choosing appropriate experimental parameters requires compromise between the spatial and temporal resolution and the dynamic range of the measurement. To explore these challenges, we do a case study on the wake of a fixed wing. The fixed model simplifies the experiment and allows direct measurements of the aerodynamic forces via load cell. We present a detailed analysis of the wake measurements, discuss the criteria for making accurate measurements, and present a solution for making quantitative aerodynamic load measurements behind free flyers.

Wallace, D. J., Picot, J. J. C. and Chapman, T. J.

"A NUMERICAL MODEL FOR FORESTRY AERIAL SPRAYING"

Agricultural and Forest Meteorology, Vol. 76, Issue 1, August 1995, pp. 19-40

A numerical model for the aerial application of pesticides in forestry aerial spraying is described. The model predicts canopy and ground deposition and drift patterns for evaporating droplets released over a forest canopy by an aircraft flying at right angles to the wind direction. Droplet trajectories are initially calculated from aircraft wake velocities. Wake velocities are generated from a second-order closure model for the turbulent transport and dissipation of aircraft vortices. When the aircraft wake has decayed to background levels of turbulence, droplet trajectory calculations are continued with a Markov type of Lagrangian model for particle dispersion in a turbulent atmosphere.

Wallace, J. M. and Foss, J. F.

"THE MEASUREMENT OF VORTICITY IN TURBULENT FLOWS"

Annual Review of Fluid Mechanics, Vol. 27, 1995, pp. 469-514.

Since Kovasznay (1950) introduced his vorticity 'meter' idea, which has been shown to be incapable of providing quantitatively reliable values of the streamwise vorticity component except in quite special circumstances, several thermal and optical anemometry methods have been developed to measure one or more components of the vorticity vector. Adequately resolving the flow in both time and space is an arduous task for all these methods. Thermal anemometry probes are limited to 'point' measurements, but they can more easily produce long time series of equally spaced data than optical methods. Such data serve, of course, to provide some new insights into the physics of turbulent flows as well as to provide statistical data for comparison to direct numerical simulations. Furthermore, it is possible to carry out experiments with these probes in flows too complex to currently simulate and at Reynolds numbers not yet attainable on the most powerful present-day computers. The optical methods, which are rapidly being refined, can now produce instantaneous planar data and are on the verge of yielding full three-dimensional field data. This review has emphasized the thermal anemometry methods because they are, to date, our principal experimental source of knowledge about statistical properties of turbulent flow vorticity fields.

Wallace, J. M. and Vukoslavcevic, P. V.

"MEASUREMENT OF THE VELOCITY GRADIENT TENSOR IN TURBULENT FLOWS"

Annual Review of Fluid Mechanics, Vol. 42, 2010, pp. 157-181.

This article reviews the principal experimental methods currently available to simultaneously measure all the terms of the velocity gradient tensor of turbulent flows. These methods have been available only for a little more than 20 years. They have provided access to the most fundamental and defining properties of turbulence. The methods include small, multisensor, hot-wire probes that provide single-location, time-resolved measurements of the tensor and various optical arrangements, most of which provide the tensor information over a larger spatial extent but, in most cases, without resolution in time. Data-reduction algorithms, spatial-resolution issues, and the use of Taylor's hypothesis are addressed in evaluating the accuracy of the various methods.

Wallin, S. and Girimaji, S. S.

"EVOLUTION OF AN ISOLATED TURBULENT TRAILING VORTEX"

AIAA Journal, Vol. 38, No. 4, April 2000, pp. 657-665

The long-time development of an isolated wing-tip turbulent vortex has been studied by Reynolds-averaged Navier-Stokes computations. The vortex is assumed to extend to infinity and to be axisymmetric and homogeneous in the axial direction, and the axial velocity is assumed to be negligible. The validity of different turbulence models, ranging from Reynolds stress transport models to eddy-viscosity K- ϵ models, has been assessed and qualitative comparisons with field measurements

are made. Reynolds stress transport models correctly predict strong suppression of the turbulence in the rotation-dominated vortex core and a reasonable decay rate of the vortex. Outside of the core, the different Reynolds stress models differ significantly. The standard eddy-viscosity K- ϵ model is insensitive to rotation and, thus, overpredicts the vortex decay rate. Computations using explicit algebraic Reynolds stress models that are strictly based on Reynolds stress transport models show that the algebraic form compares reasonably well with the full transport form. It is, however, important that the curved flow algebraic assumption is invoked when deriving the explicit algebraic model.

Wallin, S. and Girimaji, S. S.

"STUDY OF TRAILING VORTEX DECAY"

AIAA Paper No. 1999-3767, Norfolk, VA, June 1999

The long-time development of an isolated wing tip turbulent vortex has been studied by Reynolds averaged Navier-Stokes computations. The vortex is assumed to extend to infinity and to be axisymmetric and homogeneous in the axial direction, and the axial velocity is assumed to be negligible. The validity of different turbulence models, ranging from Reynolds stress transport models to eddy-viscosity models, has been assessed and qualitative comparisons with field measurements are made. Reynolds stress transport models correctly predict strong suppression of turbulence in the rotation-dominated vortex core but outside of the core the different Reynolds stress models diverge. Computations using explicit algebraic models that are strictly based on Reynolds stress transport models show that the algebraic form reasonably well compares with the full transport form. It is, however, important that the curved flow algebraic assumption is invoked in deriving the explicit algebraic model.

Walsh, Jr., R. G.

"LEADING-EDGE PRESSURE MEASUREMENTS OF AIRFOIL VORTEX INTERACTION"

NASA CR-112129, January 1970, Massachusetts Inst. of Technology, Cambridge, MA. (Also, ASRL-TR-153-1.)

Experimental pressure-differential measurements made at 10% chord of an airfoil-vortex interaction are presented. A line vortex was oscillated over an airfoil perpendicular to the span and parallel to the chord. The pressure time history was recorded to show the sharp pressure pulses resulting from the bursting of the vortex core as it impinges upon the airfoil. Results for various vortex sizes and free stream velocities were obtained. Measurements were also made when the airfoil was yawed to the line vortex. Maximum pressure differences were observed to occur in phase across the blade even with yaw, and were directly proportional to the square of the free stream velocity. The maximum dynamic pressure coefficients obtained were as high as 1.0 when vortex bursting occurred.

Wan, C. A. and Chang, C. C.

"MEASUREMENT OF THE VELOCITY FIELD IN A SIMULATED TORNADO-LIKE VORTEX USING A THREE-DIMENSIONAL VELOCITY PROBE"

Journal of the Atmospheric Sciences, Vol. 29, 1972, pp. 116-127.

A three-dimensional velocity probe, incorporating hot-film anemometry, is developed to study the mean flow field of a simulated turbulent tornado-like vortex interacting with a smooth, flat boundary. The flow characteristics are essentially controlled by a dimensionless parameter e and a Reynolds number Re . The parameter e is the ratio of sink strength to the product of the free-stream circulation and the vortex core radius. Flow fields for two different e (0.022 and 0.51) are studied, with Re greater than 100,000 in both cases. It is found that: 1) the tangential velocity profiles at more than three core radii from the axis are similar to those of a turbulent flow over a flat plate; 2) the radial velocity close to the boundary is directed inward due to a positive radial pressure gradient, while it changes direction and approaches a constant at a height of two core radii from the boundary; 3) the vertical velocity depends strongly on e and is directed downward near the vortex axis in case 1 and upward in case 2, the magnitude of the vertical velocity becoming quite small far from the axis in both cases; 4) the streamline pattern in the meridian plane has a two-celled structure for case 1 and a one-cell structure for case 2; 5) as a result of radial and axial flow, the circulation distribution is appreciably different from that of a potential vortex due to the stretching of the vortex tube; 6) zones of maximum wind speed form an annular region near the ground boundary; and 7) the maximum pressure drop, occurring at the axis, exceeds twice the core dynamic head for case 1 and 15 times for case 2 due to higher sink strength. Velocity data obtained from a real tornado are compared with the present results. Good agreement was found with case 2.

Wang, B. H., Wang, D. B., Ali, Z. A., Ting Ting, B. and Wang, H.

"AN OVERVIEW OF VARIOUS KINDS OF WIND EFFECTS ON UNMANNED AERIAL VEHICLE"

Measurement and Control, Vol 52, Issue 7-8, May 2019, pp. 731 739.

Attitude, speed, and position of unmanned aerial vehicles are susceptible to wind disturbance. The types, characteristics, and mathematical models of the wind, which have great influence on unmanned aerial vehicle in the low-altitude environment, are summarized, including the constant wind, turbulent flow, many kinds of wind shear, and the propeller vortex. Combined with the mathematical model of the unmanned aerial vehicle, the mechanism of unmanned aerial vehicle movement in the wind field is illustrated from three different kinds of viewpoints including velocity viewpoint, force viewpoint, and energy viewpoint. Some simulation tests have been implemented to show the effects of different kinds of wind on unmanned aerial vehicle's path and flight states. Finally, some proposals are presented to tell reader in which condition, which wind model should be added to simulation, and how to enhance the stability of unmanned aerial vehicle for different kinds of wind fields.

Wang, B., Liu, Z., Peng, X. and Liu, D.

"SIMULATIONS OF TIP VORTEX CAVITATION FLOWS WITH NONLINEAR k-e MODEL"

9th International Symposium on Cavitation, December 2015, Lausanne, Switzerland, Proceedings published in IOP Journal of Physics: Conference Series, Vol. 656, 2015, pp. 012187-1 to 012187-4.

Effects of turbulence models on the simulations of tip vortex wetted flows and cavitating flows are studied. Two types RANS turbulence models, with and beyond the Boussinesq turbulent-viscosity hypothesis, are investigated by examining experimental results regarding strain rate and Reynolds shear stress distributions in the vortex region. The numerical results imply that the spatial phase shift between the mean strain rate and Reynolds stresses can be accurately modeled by the nonlinear k-e turbulence model; the tip vortex cavitation region can only be predicted using the nonlinear turbulence model. The mechanism of the over-dissipation due to the turbulence model is analyzed in terms of the turbulence production, which is one of the dominant source terms in the transport equations of energy. The numerical results imply that the nonlinear k-e model is a promising candidate for predicting tip vortex cavitation flows in practical applications at a reasonable computational cost.

Wang, C. H. J. and Schluter, J.

"NEAR GROUND AIRCRAFT WAKE DISSIPATION WITH OBSTACLES"

AIAA Paper 2015-3298, June 2015, Dallas, TX.

The current study is a collaboration between the German Aerospace Center (DLR), the Nanyang Technological University, and the Civil Aviation Authority of Singapore to explore the effects of different ground-based obstacles on the evolution of near ground wake vortex. Simulations were conducted using OpenFOAM solver, and validated against the DLR water tow-tank data collected using PIV measurements. The simulation domain was scaled to match the tow tank dimensions, and the vortex pair were initialized using Lamb-Oseen vortex equation using initial circulation and core radius values from the PIV data. Simulations were conducted in the tow tank simulation domain for flat ground without obstacles and with obstacles of various configuration and design.

Wang, C. H. J., Paramasivam, S., Zhao, D., Schluter, J., Stephan, A. and Holzaepfel, F.

"OPTIMIZATION OF SINGLE OBSTACLE PAIR FOR AIRCRAFT WAKE DISSIPATION UNDER CROSSWIND CONDITION"

AIAA Paper 2017-4238, June 2017, Denver, CO.

The implementation of ground-based obstacle near the runway threshold has been shown in various simulation, experimental, and flight test studies to be an effective way of reducing the hazard of aircraft wake encounter. These plate-type obstacles functions by accelerating the formation of ground separation based secondary vortex structure (SVS), which wraps around the wake vortex core and induces early dissipation of the wake. Parameter study into the sizing of the obstacle plates has shown that the obstacle can remain effective even with reduced height. However, the effectiveness of these obstacles under crosswind condition is questionable, as previous studies have shown that the

maximum descend height of the vortex increases when subjected to crosswind. Large Eddy Simulation (LES) were carried out with vortical Reynolds number of 52,000 using a single obstacle pair of 0.05(b-zero) in height. Analysis showed that the effect of obstacle plates on wake vortex dissipation was still observed, though not as pronounced as the no-crosswind case.

Wang, C. H. J., Zhao, D., Schluter, J., Holzaepfel, F. and Stephan, A.

"LES STUDY ON THE SHAPE EFFECT OF GROUND OBSTACLES ON WAKE VORTEX DISSIPATION"

Aerospace Science and Technology, Vol. 63, 2017, pp. 245-258.

The lingering wake vortex following a landing aircraft has long been a hazard to aviation safety. Previous studies at the German Aerospace Center (DLR) confirmed the effectiveness of applying ground-based obstacles to improve the dissipation of the wake vortex pair by triggering the onset of the vortex bursting by the artificial introduction of shortwave instability. Following the design of the plate line obstacles as proposed by DLR for vortex dissipation, we further investigate the influence of the shape of the ground obstacles on dissipating wake vortex in the present work. The secondary vortex structure, resulting from the interaction between the vortical flow and the obstacle plate, stems from the location of the obstacle and travels outward along the vortex axis, thus spreading instability to the vortex structure along the way. 3D numerical simulations were conducted using Large Eddy Simulation with OpenFOAM solver. The numerical solutions were first compared to the experimental vortex measurement performed in DLR's Wasser Schleppkanal Gottingen tow-tank. In addition to the baseline setup three different shaped obstacles were numerically tested and compared in the simulation. The numerical results reveal that 50 percent reduction of the wake dissipation, measured with the circulation of the vortex, was achieved within $t^* = 1.5$ compared to $t^* > 4.0$ in the absence of ground obstacle. The present study showed that the shape of the obstacles affects the pattern of the secondary vortex structure created, and the resulting drag force acting on the obstacle has a more direct effect on wake dissipation.

Wang, C. H. J., Zhao, D., Schluter, J., Stephan, A. and Holzaepfel, F.

"EFFECT OF GROUND OBSTACLE OF DIFFERENT ASPECT RATIO ON WAKE VORTEX DISSIPATION"

AIAA Paper 2016-3134, June 2016, Washington, DC.

The employment of obstacles to accelerate dissipation of aircraft wake vortex near ground was proposed by DLR, with several subsequent studies on the effect of the obstacles under different atmospheric conditions. In collaboration with DLR, the NTU research team employed large eddy simulation to study the effect of obstacle shape on the dissipation rate and propagation speed of vortex breakup. Simulation results have shown that while the shape of the obstacle influences the propagation speed of vortex breakup, the flow-facing area of the obstacles is the major contributing factor deciding the magnitude of circulation reduction on top of the obstacle. The current study aims to investigate the effect of the aspect ratio of obstacle on vortex dissipation while holding the biggest contributor to reduction of circulation, form drag from the obstacle projected area, constant. Out

simulation data has shown that, with every other parameter remained constant, the aspect ratio of obstacle makes negligible difference to the dissipation rate of wake vortex. The result suggested that the height of the obstacle could be further reduced into a less intrusive profile and lessen the impact of these obstacles on airport operations.

Wang, C. H. J., Zhao, D., Schluter, J., Stephan, A. and Holzaepfel, F.

"COMPUTATIONAL INVESTIGATION OF VARYING PLATE-LINE GEOMETRY AND PLACEMENT ON WAKE VORTEX DISSIPATION"

Journal of Aircraft, Vol. 55, No. 1, January-February 2018, pp. 133-144.

One of the bottlenecks for the recent increase in air traffic density is near the airport, where wake vortices, bounded by the terrain, could easily rebound into the landing corridor and remain there for a long period of time while maintaining their strength. The threat of near-ground wake vortex could be mitigated by the plate-line technology, which places a series of thin plates across the landing corridor before the runway; the technology was shown to significantly reduce the time it takes for wake vortex dissipation. The current investigation aims to better understand factors such as plate dimension and lateral position influences on the generation of secondary vortex structure and ultimately the dissipation rate of a wake vortex pair. It is found that the wake dissipation could be sped up further by optimizing the lateral position of the plate relative to the obstacle-vortex contact location, while the height of the plate could be significantly reduced without noticeably affecting the performance of the obstacle set.

Wang, C. M., Steinhoff, J. S. and Stremel, P. M.

"A NEW NUMERICAL APPROACH FOR ROTORCRAFT AERODYNAMICS USING VORTICITY CONFINEMENT"

AIAA Paper No. 1997-2328, Atlanta, GA, June 1997

The Vorticity Confinement method is used in conjunction with uniform Cartesian grids for computing flows of blunt bodies. These bodies are defined on the uniform grid by a smooth function where the function is designated zero on the body surfaces. A unique computation procedure is applied to all the grid points with the confinement performed outside the body based on the vorticity whereas inside the body based on the function. For flows around streamline-like bodies, such as a wing, the computation is performed on body-fitted grids where these grids can be encompassed by the uniform grid. Flow information is transferred between the body-fitted grids and the uniform grid, where one or more blunt bodies are embedded, through an overset grid technique. However, there is no hole-cutting needed since the solid bodies are explicitly defined by the smooth function. A NACA0012 wing download under a rotor is computed by the combined approach with a generic nacelle at the wing tip.

Wang, C. M., Steinhoff, J. S. and Wenren, Y.

"NUMERICAL VORTICITY CONFINEMENT FOR VORTEX-SOLID BODY INTERACTION PROBLEMS"

AIAA Journal, Vol. 33, No. 8, August 1955, pp. 1447-1453

A new numerical method based on adding a term to the Euler/Navier-Stokes equations has demonstrated that it can effectively treat vortex-dominated flows using low-order numerical schemes and coarse grids. With the technique, numerical diffusion introduced by convection schemes can be eliminated when solving the modified flow governing equations. The modification of the velocity field, which conserves the total vorticity, essentially convects the vorticity toward its local extreme to offset the numerical diffusion. This method preserves the vortex structure even when vortices travel through a coarse grid region. The method is implemented separately with two distinctive basic solvers: a Navier-Stokes flow solver based on a vorticity-velocity formulation and an Euler solver based on a velocity-pressure formulation. Problems presented in this paper include airfoil dynamic stall, vortex-airfoil interaction, and vortex-fuselage interactions.

Wang, F. Y. and Sforza, P. M.

"AN EXPLORATORY WIND TUNNEL STUDY OF SUPERSONIC TIP VORTICES"

AIAA Paper No. 1993-2923, Orlando, FL, July 1993

Results of recent tests conducted at Polytechnic University on supersonic tip vortices generated by a small aspect ratio, rectangular half-wing in a Mach 3 stream are presented. Surveys were made for two angles of attack at a station approximately two chords downstream of the half-wing. Time-averaged vortex position, Mach number, velocity, pressure, and density were estimated by combining pitot pressure readings and a shadowgraph-based visualization technique. Some very low frequency vortex trajectory oscillations were observed. In many respects, the observed supersonic tip vortex behaved much like its low-speed counterpart with a compressibility correction, that is, a two-dimensional vortex superimposed on a uniform freestream velocity. The downstream convection of the vortex appeared to proceed with negligible diffusion in the near field studied. It was also found that the trailing supersonic tip vortices, although estimated to be weak in terms of swirl, appear to include a substantial stagnation pressure deficit. On the other hand, it appears that the axial component of velocity and the temperature are constant across the profile, within the spatial resolution possible. Suggestions on vortex modeling are provided to aid in formulating initial conditions for numerical studies involving supersonic tip vortices.

Wang, F. Y. and Zaman, K. B. M. Q.

"AERODYNAMICS OF A JET IN THE VORTEX-WAKE OF A WING"

AIAA Paper No. 2001-1119, Reno, NV, January 2001

Results of a low-speed experimental investigation of jet behavior in the trailing vortex-wake of a wing are presented. The effects of varying jet-to-freestream velocity ratio and vortex-wake strength on the downstream evolution of the flow field are quantified via three-dimensional hot-wire anemometry surveys. Under conditions encountered in powered flight, especially during take-off, landing and maneuvering of a vehicle, the jet is found to undergo severe distortion within a very short distance

from the nozzle exit. The interaction of the jet and the wing vortices generates additional vortical structures. Spreading and decay of the jet are shown to be governed predominantly by the interaction of the vortices.

Wang, F. Y. and Zaman, K. B. M. Q.

"AERODYNAMICS OF A JET IN THE VORTEX WAKE OF A WING"

AIAA Journal, Vol. 40, No. 3, March 2002, pp. 401-407.

Results of a low-speed experimental investigation of jet behavior in the trailing vortex wake of a wing are presented. The effects of varying jet-to-freestream velocity ratio and vortex-wake strength on the downstream evolution of the flowfield are quantified via three-dimensional hot-wire anemometry surveys. Under conditions encountered in powered flight, especially flow states characteristics of takeoff, landing, and maneuvering of a vehicle, the jet is found to undergo severe distortion within a very short distance from the nozzle exit. The interaction of the jet and the wing vortices generates additional vortical structures. Spreading and decay of the jet are shown to be governed predominantly by the interaction of the vortices.

Wang, F. Y., Sforza, P. M. and Pascali, R.

"VORTEX-WAKE CHARACTERISTICS OF A HIGH SPEED CIVIL TRANSPORT TYPE WING PLANFORM AT MACH 2.5"

AIAA Paper No. 1995-2284, San Diego, CA, June 1995

An experimental study of the vortex-wake flow of a High-Speed Civil Transport (HSCT) baseline type planform in a Mach 2.5 stream is presented. Surface oil flow visualization was used to indicate certain features of the flow over the wing (Reynolds number based on mean aerodynamic chord was 4.04 million), while spark-shadowgraphs and laser light sheets were used to provide visual information on vortex-wake development up to 11 tip chords downstream of the trailing edge. In addition, pitot pressure surveys were made at 1.3, 7.8 and 16.3 tip chords downstream of the model to map out the trajectory and decay characteristics of the vortex-wake. It was found that three well-defined swirling structures are generated by the representative HSCT planform tested. These results indicate that even for a typical angle of attack of 5 degrees, vortices of substantial strength are generated. The vortex core diameters are observed to persist, essentially unchanged, up to the maximum visual range allowed. The results of the pitot survey demonstrated that the vortices generated are still quite noticeable as far as 16.3 tip chords downstream; in particular, the strength of the tip vortex was virtually unchanged over the entire surveyed range of 16.3 tip chords.

Wang, F. Y., Sforza, P. M. and Pascali, R.

"VORTEX-WAKE CHARACTERISTICS OF A SUPERSONIC TRANSPORT WING PLANFORM AT MACH 2.5"

AIAA Journal, Vol. 34, No. 8, 1995, pp. 1750-1752

An experimental study of the vortex-wake flow of a High-Speed Civil Transport (HSCT) type crank-arrow planform in a Mach 2.5 stream is presented. It is found that three well-defined swirling structures are generated by the representative HSCT planform tested. These are respectively, vortices from wing tip, leading-edge separation from the delta-wing portion and that from the junction of the crank-arrow planform. The Pitot pressure survey suggested that the wing tip vortex would persist farther downstream compared to the other two vortices shed from the planform. The exploratory wake survey also suggested that the application of an incompressible roll-up model could be a viable approach for calculating the vortex-wake evolution from supersonic aircraft, provided that a realistic wing loading on the planform is available to initialize the subsequent vortex-wake computation.

Wang, F. Y., Wassaf, H. S., Gulsrud, A., Delisi, D. P. and Rudis, R. P.

"ACOUSTIC IMAGING OF AIRCRAFT WAKE VORTEX DYNAMICS"

AIAA Paper No. 2005-4849, Toronto, Canada, June 2005

The experience in utilizing a phased microphone array to passively image aircraft wake vortices is highlighted. It is demonstrated that the array can provide visualization of wake dynamics like smoke release or natural condensation of vortices. Examples on how the technique has been integrated with other data to address some of the research issues in wake vortices are documented. These topics include the initial vortex spacing characterization, collaboration with simultaneous pulsed Lidar data to provide a more complete understanding of vortices at a late stage in their evolution, and correlation between atmospheric turbulence with the time-scale involved for vortices developing into a very contorted state. In addition, the paper provides a comparison between the vortex tracks as inferred from their acoustics characteristics vs. those detected from the velocity field (i.e., pulsed Lidar). A preliminary attempt is also made to examine the global link between wake vortex sound and vortex circulation, suggesting that there could be a power law relationship between the two datasets.

Wang, F. Y., Wassaf, H., Dougherty, R. P., Clark, K., Gulsrud, A., Fenichel, N. and Bryant, W. H.

"PASSIVE WAKE ACOUSTICS MEASUREMENTS AT DENVER INTERNATIONAL AIRPORT"

4th NASA Integrated CNS Conference and Workshop, Fairfax, VA, April 2004

From August to September 2003, NASA conducted an extensive measurement campaign to characterize the acoustic signal of wake vortices. A large, both spatially as well as in number of elements, phased microphone array was deployed at Denver International Airport for this effort. This paper briefly describes the program background, the microphone array, as well as the supporting ground-truth and metrological sensor suite. Sample results to date are presented and discussed. It is seen that, in the frequency range processed so far, wake noise is generated predominantly from a very confined area around the cores.

Wang, H.

"SHORT WAVE INSTABILITY ON VORTEX FILAMENTS"

Physical Review Letters, Vol. 80, No. 21, May 1998, pp. 4665-4668

The short-wave instability on corotating vortex filaments is investigated. It is shown that the short-wave instability always occurs on corotating vortex filaments of fixed core structure. Moreover, when the interfilament distance is smaller than or comparable to the core size, vortex filaments produce short wave unstable modes which lead to wild stretching and folding; when vortex filaments are far apart from each other, unstable modes are bounded by a fraction of the core size and the vortex stretching remains bounded. These findings may be used to explain the smooth behavior of superfluid vortices. They also explain the stretching seen in numerical calculations.

Wang, H., Cai, L., Chong, X. and Geng, H.

"EXPERIMENTAL STUDY OF THE JET ENGINE EXHAUST FLOW FIELD OF AIRCRAFT AND BLAST FENCES"

Promet - Traffic & Transportation, Vol. 27, No. 2, 2015, pp. 181-190.

A combined blast fence is introduced in this paper to improve the solid blast fences and louvered ones. Experiments of the jet engine exhaust flow (hereinafter jet flow for short) field and tests of three kinds of blast fences in two positions were carried out. The results show that the pressure and temperature at the center of the jet flow decrease gradually as the flow moves farther away from the nozzle. The pressure falls fast with the maximum rate of 41.7%. The dynamic pressure 150 m from the nozzle could reach 58.8 Pa, with a corresponding wind velocity of 10 m/s. The temperature affected range of 40 deg C is 113.5x20 m. The combined blast fence not only reduces the pressure of the flow in front of it but also solves the problems that the turbulence is too strong behind the solid blast fences and the pressure is too high behind the louvered blast fences. And the pressure behind combined blast fence is less than 10 Pa. The height of the fence is related to the distance from the jet nozzle. The nearer the fence is to the nozzle, the higher it is. When it is farther from the nozzle, its height can be lowered.

Wang, J. J., Li, Y. C. and Choi, K.-S.

"GURNEY FLAP -- LIFT ENHANCEMENT, MECHANISMS AND APPLICATIONS"

Progress in Aerospace Sciences, Vol. 44, 2008, pp. 22-24.

Since its invention by a race car driver Dan Gurney in 1960s, the Gurney flap has been used to enhance the aerodynamics performance of subsonic and supercritical airfoils, high-lift devices, and delta wings. To take stock of recent research and development of Gurney flap, we have carried out a review of the characteristics and mechanisms of lift enhancement by the Gurney flap and its applications. Optimum design of the Gurney flap is also summarized in this paper. For the Gurney flap to be effective, it should be mounted at the trailing edge perpendicular to the chord line of airfoil or wing. The flap height must be of the order of local boundary layer thickness. For subsonic airfoils, an

additional Gurney flap increases the pressure on the upstream surface of the Gurney flap, which increases the total pressure of the lower surface. At the same time, a long wake downstream of the flap containing a pair of counter-rotating vortices can delay or eliminate the flow separation near the trailing edge on the upper surface. Correspondingly, the total suction on the airfoil is increased. For supercritical airfoils, the lift enhancement of the Gurney flap mainly comes from its ability to shift the shock on the upper surface in the downstream. Applications of the Gurney flap to modern aircraft design are also discussed in this review.

Wang, J., Zhang, L., Dai, A., Immler, F., Sommer, M. and Vomel, H.

"RADIATION DRY BIAS CORRECTION OF VAISALA RS92 HUMIDITY DATA AND ITS IMPACTS ON HISTORICAL RADIOSONDE DATA"

Journal of Atmospheric and Oceanic Technology, Vol. 30, February 2013, pp. 197-214.

The Vaisala RS92 radiosonde is the most widely used type of sonde in the current global radiosonde network. One of the largest biases in the RS92 humidity data is its daytime solar radiation dry bias (SRDB). An algorithm [referred to as NCAR radiation bias correction (NRBC)] was developed to correct the SRDB based on a more complicated algorithm developed by the Global Climate Observing System (GCOS) Reference Upper-Air Network (CRUAN). The NRBC to relative humidity (RH) is a function of the measured RH and temperature, and the temperature solar radiation correction. The latter varies with pressure, season, and time of the day. The RH correction has a mean magnitude of about 2-4 percent and 6-8 percent in the lower-midtroposphere and upper troposphere, respectively. The NRBC is evaluated against the GRUAN-corrected RS92 data and the ground-based GPS-estimated precipitable water (PW). The corrected RH agrees with the GRUAN data within ± 0.5 percent on average, with standard deviations of about 1-2 percent and 2-6 percent in the lower-midtroposphere and upper troposphere, respectively. The NRBC leads to reduced mean biases, and better agreement with the GPS PW and its diurnal cycle. The NRBC has been applied to historical radiosonde data at 65 stations. The radiosonde humidity data, both with and without the NRBC, are homogenized using the method of Dai et al. (2011). The NRBC results in consistently elevated RHs throughout the whole record in the homogenized data. This could have a significant impact on global reanalysis products when they are assimilated into the reanalysis models. However, the NRBC has insignificant effects on the long-term trends as the correction is primarily for mean biases.

Wang, L., Hu, R., Zhang, J. and Ma, Y.

"ON THE VORTEX DETECTION METHOD USING CONTINUOUS WAVELET TRANSFORM WITH APPLICATION TO PROPELLER WAKE ANALYSIS"

Mathematical Problems in Engineering, Vol. 2015, Article 242917, pp. 1-9.

The method based on the continuous wavelet transformation to detect and characterize two-dimensional vortex is analyzed for a synthetic flow and applied to vortex detection of propeller wake. The characteristics of a vortex, such as center location, core radius, and circulation, are extracted based

on the Lamb-Oseen and Rankine vortex models, the latter of which is a novel attempt. The effects of various factors such as the difference scheme, the grid and scale discretization, transform variable, and vortex model on vortex detection have been investigated thoroughly. The method is further applied to identify the tip vortex in a propeller wake.

Wang, L., Xu, G. and Shi, Y.

"HIGH-RESOLUTION SIMULATION FOR ROTORCRAFT AERODYNAMICS IN HOVERING AND VERTICAL DESCENDING FLIGHT USING A HYBRID METHOD"

Chinese Journal of Aeronautics, Vol. 31, No. 5, 2018, pp. 1053-1065.

A high-resolution simulation tool for rotorcraft aerodynamics is developed by coupling CFD with a Vorticity Transport Model (VTM). A Eulerian-based CFD module is used to model the blade near body flowfield, and a Lagrangian-based VTM module is employed for vortex tracking in the far wake. The coupling procedure is implemented by transmitting vortex sources to the VTM module and feeding boundary conditions back to the CFD module. The presented CFD/VTM hybrid solver is firstly validated by hover cases of three different rotor configurations. Simulation results, including the blade surface pressure distribution, rotor downwash, and hover figure of merit, exhibit favorable correlations with available experimental data. Then, a rotor operated in vertical descending flight with a fixed collective pitch is investigated. It is shown that the CFD/VTM coupling method is suitable for rotor wake simulation. Wake instabilities (far wake breakdown in hover and toroidal wake pattern in the vortex ring state) are successfully demonstrated with a moderate computational cost.

Wang, S. and Rusak, Z.

"AXISYMMETRIC VORTEX BREAKDOWN IN A PIPE"

ESAIM: Proceedings, Vol. 1, 1996, pp. 267-278.

A recent theory of the nearly axisymmetric vortex breakdown in a pipe is presented. We study the motion of an axisymmetric and inviscid swirling flow in a pipe with certain boundary conditions that may reflect the physical situation. The theory is built of global analysis of solutions of the Squire-Long equation and linear stability analysis of these solutions. The theory unifies the major previous theoretical approaches and provides for the first time a consistent explanation of the physical mechanism leading to the vortex breakdown phenomenon as well as the conditions for its occurrence.

Wang, T., Dooland, C. J., Coton, F. N. and Galbraith, A. M.

"EXPERIMENTAL STUDY OF THE THREE DIMENSIONALITY OF ORTHOGONAL BLADE-VORTEX INTERACTION"

AIAA Journal, Vol. 40, No. 10, October 2002, pp. 2037-2046

Wind-tunnel tests were conducted to investigate orthogonal vortex interaction with a stationary blade mimicking the main-rotor/tail-rotor interaction. High-quality experimental results with high-temporal resolution for the interaction have been obtained at different wind speeds and blade incidence angles. A vortex generator was specially designed for the experiment and produced stable trailing vortices. These were identified by hot-wire anemometry, with different vortical parameters for different speeds. When the measurement location is aligned with the vortex axis, pressure data reveal a suction peak on the upper blade surface and a pressure peak on the lower surface during the interaction. Significant dependence of the pressure on spanwise distance from the vortex indicates a strong three-dimensional interaction effect. For example, for spanwise positions above the core axis, a pressure pulse on the upper surface and a suction peak on the lower surface have been observed. It is shown that these differences can be attributed to the influence of the axial and tangential velocity components of the vortex. Pressure data for the blade at high incidence also show that the interaction can exacerbate and alleviate flow separation, depending on the spanwise position.

Wang, T.-I.

"OPTICAL SCINTILLOMETER WAKE VORTEX DETECTION SYSTEM"

U.S. Patent 5838007, November 1998

An optical scintillometer is provided which is operative to measure atmospheric wake vortex turbulence intensity up to a distance of ten kilometers. The optical scintillometer provides real time continuous measurements of aircraft generated wake vortex turbulence intensity in the field of operations employing a transmitter, receiver, and digital processing circuitry. The signal is digitized before comparison with a threshold to eliminate events attributable to objects moving through the path of the optical transmitter and receiver. The system is thereby able to perform calculations to adjust the first order log-amplitude variance function in the saturation regime. An extremely important aspect of the invention is the digitization of the signal and its comparison with the threshold signal. Because a digital signal is compared with a threshold signal level, invalid signal inputs are excluded from the calculation of path-averaged turbulence intensity. The exclusion of such signals assures the data quality in computing the refractive turbulence intensity even when there is an interruption of the infrared beam. This feature is critical for the data processing. Data produced when the optical path is obstructed by moving vehicles, pedestrians, and airplanes is not used for processing to protect the quality of the output measurements.

Wang, X., Li, J., Qu, L., Pang, C. and Niu, F.

"TEMPORAL EVOLUTION OF THE RCS OF AIRCRAFT WAKE VORTICES"

Aerospace Science and Technology, Vol. 24, 2013, pp. 204-208.

Knowledge of the radar scattering characteristics is one of the key issues for the development of wake vortex detection technology. This paper studies the temporal evolution of the RCS (radar cross-section) of wake vortices. The RCS-time plot is observed to increase as a whole and step at a certain time. These

properties could provide help to the design of wake vortex detection radar and the optimization of radar station layout. The special spiral structures within the wake, together with the Bragg scattering theory, are used to well explain these phenomena, and some representative radar experiments are also included to verify them.

Wang, Y.

"A METHOD OF ESTIMATING AIRPLANE TURBULENCE USING WIND DATA"

ICAS 2002, Paper 2002-P15, Sept. 2002, Toronto, Canada.

Using the nonlinear Boussinesq equations, the analysis of the relations between the wind and the turbulence kinetic energy (TKE) development is made, and a method of estimating the airplane turbulence using the wind data is obtained. Wind is closely related to the appearance of turbulence and its development. Under a certain condition, wind shear can produce turbulence, and whether the turbulence can be developed is decided by the distribution of wind.

Wang, Y., Liu, P., Hu, T., Qu, Q., Chen, Q. and Akkermans, R.

"EXPERIMENTAL INVESTIGATIONS ON THE INTERACTION OF THE SINGLE/CO-ROTATING VORTEX WITH THE GROUND"

AIAA Journal, Vol. 57, No. 2, February 2019, pp. 499-512.

Experiments on the interactions between a single vortex/co-rotating vortex and the ground were conducted in a water channel using particle image velocimetry (PIV) measurements. Both the single vortex (SNV) and co-rotating vortex pair (CVP) were generated by using NACA0012 vortex generators to simulate the main flow features behind one side of the wings at the far field and near field. The ground effect was achieved by allocating a flat plate downstream of the vortex generators. It has been found that the lower initial vortex height led to greater vortex rebound and lateral drift in both the SNV and CVP cases, whereas the development of a secondary vortex was also promoted with lower initial vortex height. In the CVP cases, the mutual rotation of the primary vortices led to variation of the close-to-wall velocity distribution. This effect added the disturbances to the formation and evolution of the secondary vortical structure, which eventually affected the height of the secondary vorticity and the rebound of the primary vortices.

Wang, Y., Miller, D. R., Anderson, D. E. and McManus, M. L.

"A LAGRANGIAN STOCHASTIC MODEL FOR AERIAL SPRAY TRANSPORT ABOVE AN OAK FOREST"

Agricultural and Forest Meteorology, Vol. 76, Issues 3-4, October 1995, pp. 277-291.

An aerial spray droplets' transport model has been developed by applying recent advances in Lagrangian stochastic simulation of heavy particles. A two-dimensional Lagrangian stochastic model was adopted to simulate the spray droplet dispersion in atmospheric turbulence by adjusting the

Langrangian integral time scale along the drop trajectory. The other major physical processes affecting the transport of spray droplets above a forest canopy, the aircraft wingtip vortices, and the droplet evaporation, were also included in each time step of the droplets' transport. The model was evaluated using data from an aerial spray field experiment. In generally neutral stability conditions, the accuracy of the model predictions varied from run-to-run as expected. The model prediction was adequate in two-dimensional steady wind conditions, but was less accurate in variable wind condition. The results indicated that the model can simulate successfully the ensemble; average transport of aerial spray droplets under neutral, steady atmospheric wind conditions.

Wang, Y., Qin, S. and Liu, H.

"VORTEX DRAG GENERATED BY AIRCRAFT AFTERBODY VORTICITY-LOOP SYSTEM"

AIAA Paper 2018-0550, January 2018, Kissimmee, FL.

High cruise resistance exerted on the aircraft afterbody is mainly due to a vortex system, which is composed of afterbody vorticity-loop (ABVL) and co-rotating horizontal tail tip vorticity-loop (HTVL). This lift-generated vortex system is associated with the specific viscosity-independent portion of overall drag, which is determined as vortex drag. In this paper, the vortex system of the aircraft afterbody has been investigated using particle image velocimetry (PIV) experiment and improved delayed detached eddy simulation (IDDES). Conventionally, the induced drag is regarded as a steady case of vortex drag without considering vortex interactions. It has been computed with Betz and Maskell wake-integral model to conduct a comparative analysis, which has demonstrated the nonnegligible role played by the non-linear part. To reveal the underlying physical source and meaning of vortex drag, the Vorticity Moment Theorem (VMT) has been developed and applied into the single and multiple vorticity-loop model to quantitatively define and accurately understand vortex drag.

Wang, Y., White, M. and Barakos, G.

"WIND TURBINE WAKE ENCOUNTER STUDY"

Report, March 2015, University of Liverpool, Liverpool, UK.

The wake vortices generated by a wind turbine or a wind farm could cause interference with passing light aircraft. A wind turbine study using engineering wake modelling, CFD, LIDAR field measurements and piloted flight simulations was carried out at University of Liverpool in collaboration with CAA, UK. A modified Kocurek wind turbine wake model has been developed to simulate wind turbine wakes. It has been validated using the MEXICO wind turbine and the PIV wind tunnel measurements, as well as CFD wake simulation results. This wake vortex model was applied to a WTN250 wind turbine that is installed near the East Midlands Airport, UK, where field measurements of wind turbine wake using LIDAR were carried out. The LIDAR data was compared with the wake velocity fields generated by different wake modelling methods. The WTN250 wind turbine wake velocities generated by the Kocurek wake vortex model were integrated into an aircraft flight dynamic model to simulate a wind turbine wake encounter scenario, designed for a light aircraft approaching an airport, where a wind

turbine was installed. The severity of the wind turbine wake encounter was investigated using piloted flight simulations. The simulation results suggest that the wake generated minor upsets on the aircraft and resulted a severity rating of B if only the disturbances caused by wake velocity deficits were considered. Off-line simulations and analysis of wind turbine wake encounters were also carried out and the results indicated that for the small size WTN250 wind turbine, the approach based on the Beddoes circulation formula appeared to give predictions in line with the LIDAR measurements. The off-line analysis also showed the variability of the predictions based on the employed wake models.

Wang, Y., White, M. and Barakos, G.

"HELICOPTER WAKE ENCOUNTER STUDY"

Report, March 2015, University of Liverpool, Liverpool, UK.

Different methods of modelling helicopter wakes, namely, a hybrid wake model, a free wake model and a CFD actuator disk model are presented and compared with available wind tunnel and flight test data. The free wake model was then used to generate the wake vortices of a helicopter in hover-taxiing over an airport runway. A hybrid wake model, with a wake decay law, was also used to generate the far wake of a helicopter in level flight. The wake induced velocity fields were integrated into an aircraft flight dynamics model and piloted flight simulations were carried out to study a light aircraft encountering a helicopter wake during landing and level flight. It was found that for the current landing wake encounter scenario, the existing wake encounter criteria and severity metrics for the determination of the hazardous distance might not be appropriate if the wake encounter occurs close to the ground. The landing simulation results suggest that for a helicopter in low-speed hover-taxiing (less than 40 kt airspeed), the wake encounter detectable horizontal distance is about three times the diameter of the rotor, which coincides with the current safety guidelines of the Civil Aviation Authority of the UK. The level flight simulations revealed the effects of the vertical separation distance and of the wake decay on the encounter severity.

Wang, Y., White, M. and Barakos, G. N.

"WIND-TURBINE WAKE ENCOUNTER BY LIGHT AIRCRAFT"

Journal of Aircraft, Vol. 54, No. 1, January-February 2017, pp. 366-369.

Wake-field measurements using LIDAR were carried out on a WTN250 wind turbine located at the East Midlands Airport in the United Kingdom. The measurements captured the wake flow patterns in terms of wake induced mean velocity deficit and indicated that, for this wind turbine, the mean wake velocities recovered to the freestream wind speed at a position about five rotor diameters downstream. The LIDAR measurements were compared with the results of a full CFD simulation, which was conducted on the MEXICO wind turbine with a similar tip speed ratio, and were also compared with the wind-turbine velocity deficit wake models. In general, reasonable agreement was shown. The piloted flight simulation results suggest that the WTN250 wind-turbine wake mainly generated yaw disturbances on the encountering aircraft of less than 10 deg. The wake-encounter severity was

regarded as minor. The wake model and the LIDAR measurements can only generate the wake velocity deficit flowfields. The mean velocity deficits in wind-turbine wakes normally decay faster than that of the wake turbulence. The wake turbulence persists farther downstream. If the length scales of the wake turbulence are comparable with the size of aircraft lifting surfaces, it could cause unsteady upsets on the encountering aircraft. Methods of modeling and measuring wind-turbine wake turbulence will be sought and implemented in future wake-encounter flight simulations.

Wang, Y., White, M., Barakos, G. N., Tormey, P. and Pantazopoulou, P.

"SIMULATION OF A LIGHT AIRCRAFT ENCOUNTERING A HELICOPTER WAKE"

Journal of Aircraft, Vol. 52, No. 2, March-April 2015, pp. 510-523.

Different methods of modeling helicopter wakes are presented and compared with available wind-tunnel and flight-test data. A free-wake model was then used to generate the wake vortices of a helicopter hover-taxiing over an airport runway. A hybrid wake model, with a wake decay law, was also used to generate the far wake of a helicopter in level flight. The wake-induced velocity fields were integrated into an aircraft flight dynamics model, and piloted flight simulations were carried out to study a light aircraft encountering a helicopter wake during landing and level flight. It was found that, for the current landing wake-encounter scenario, the existing wake-encounter criteria and severity metrics for the determination of the hazardous distance might not be appropriate if the wake encounter occurs close to the ground. The landing simulation results suggest that, for a helicopter in low-speed hover-taxiing (less than 40 kt airspeed), the wake-encounter detectable horizontal distance is about three times the diameter of the rotor, which coincides with the current safety guidelines of the Civil Aviation Authority of the United Kingdom. The level-flight simulation revealed the effects of the vertical separation distance and of the wake decay on the encounter severity.

Wang, Y., White, M., Barakos, G. N., Wheeler, S., Tormey, P. and Pantazopoulou, P.

"WIND TURBINE WAKE ENCOUNTER BY LIGHT AIRCRAFT"

40th European Rotorcraft Forum, Paper 084, September 2014, Southampton, UK.

The wake vortices generated by a wind turbine or a wind farm could interference with passing-by flying vehicles. A wind turbine wake study using engineering wake modelling, CFD, LIDAR field measurement and piloted flight simulation are carried out at University of Liverpool in cooperation with CAA, UK. A modified Kocurek wind turbine wake vortex model has been developed to simulate wind turbine wakes. It has been validated on the MEXICO wind turbine with the PIV wind tunnel measurements and the full CFD wake simulation results. The wake vortex model was applied to a WTN250 wind turbine, which has been installed near the East Midlands Airport, UK, where field measurements of wind turbine wake using LIDAR were carried out. The LIDAR measurement data were compared with the wake velocity fields generated by different wake modelling methods. The WTN250 wind turbine wake velocities generated by the Kocurek wake vortex model were integrated into an aircraft flight dynamic model to simulate a wind turbine wake encounter scenario, designed for a light

aircraft approaching an airport, where a wind turbine was installed. The severity of the wind turbine wake encounter was investigated using piloted flight simulations. The simulation results suggest that the wake generated minor upsets on the aircraft and resulted a severity rating of B if only the disturbances caused by wake velocity deficits were considered.

Wang, Z.

"NUMERICAL MODELING OF CHEMISTRY, TURBULENT MIXING AND AEROSOL DYNAMICS IN NEAR-FIELD AIRCRAFT PLUMES"

Ph.D. Thesis, University of California at Berkeley, Berkeley, CA, 1998.

A detailed mechanism including gas phase HO_x, NO_x, SO_x, and CO_x chemistry between the aircraft exhaust and the ambient air in near-field aircraft plumes is compiled. A reduced mechanism capturing the major chemical pathways is developed. Predictions by the reduced mechanism is found to be in good agreement with those by the detailed mechanism. With the reduced chemistry, the computer CPU time is saved by a factor of more than 3.5 for the near-field plume modeling. Distributions of major chemical species are obtained and analyzed. Sensitivities of major species with respect to reaction step are deduced for identification of the dominant gas phase kinetic reaction pathways in the jet plume.

Wang, Z., Tian, W. and Hu, H.

"AN EXPERIMENTAL STUDY ON THE WAKE CHARACTERISTICS OF DUAL-ROTOR WIND TURBINES BY USING A STEREOSCOPIC PIV TECHNIQUE"

AIAA Paper 2016-3128, June 2016, Washington, DC.

An experimental study was performed to investigate the wake characteristics behind an innovative dual-rotor wind turbine (DRWT) with co- and counter-rotating configurations, in comparison with those of a traditional single-rotor wind turbine (SRWT). The comparative study was performed in a large-scale Atmospheric Boundary Layer (ABL) wind tunnel with the scaled DRWT and SRWT models under neutral stability conditions. In addition to measuring the power outputs of the DRWT and SRWT systems, static and dynamic wind loads acting on the test models were also investigated to assess the effects of the secondary, smaller, co-axial rotor in either counter-rotating (rotors rotate at opposite directions) or co-rotating (rotors rotate at same direction) configuration on the power production performance and the resultant dynamic wind loads (both aerodynamic forces and bending moments) acting on the DRWT models. Furthermore, a high-resolution stereoscopic Particle Image Velocimetry (Stereo-PIV) system was also used to make both 'free-run' and 'phase-locked' measurements to quantify the transient behavior (i.e., formation, shedding and breakdown) of unsteady wake vortices and the flow characteristics behind the DRWT and SRWT models. The detailed flow field measurements were correlated with the power output data and dynamic wind loading measurements to elucidate underlying physics for higher total power yield and better durability of wind turbines operating in turbulent non-homogeneous atmospheric boundary layer winds.

Wang, Z., Wang, J. and Shortle, J.

"SENSITIVITY ANALYSIS OF POTENTIAL WAKE ENCOUNTERS TO STOCHASTIC FLIGHT-TRACK PARAMETERS"

5th International Conf. on Research in Air Transportation, May 2012, Berkley, CA.

Many NextGen technologies and concepts, when implemented, will change the underlying stochastic nature of flight tracks. This paper investigates how changes in the stochastic variability of flight tracks have the potential to impact the probability of potential wake encounters. We investigate these relationships for a single runway and for parallel runways. The results show that the mean and standard deviation of separation, and the vertical standard deviation are the key parameters affecting potential wake encounters. In the parallel-runway scenario, effects of crosswind and runway spacing are studied. A full factorial design is conducted to estimate the impact of parameters and their interactions, with dominating factors identified. In some cases, results can be different even for the same parameter when different circulation thresholds are used for defining wakes. Outputs from different wake models (TDAWP vs. D2P) are compared. The overall objective is to assess the sensitivity of these results to parameters of the stochastic input distribution.

Ward, D. T. and Myatt, J. H.

"PRELIMINARY DESIGN OF AN INTERMITTENT SMOKE FLOW VISUALIZATION SYSTEM"

NASA-CR-186027, January 1993, NASA Dryden Flight Research Center, Edwards, CA.

A prototype intermittent flow visualization system has been designed to study vortex flow field dynamics and has been constructed and tested through its ground test phase. It produces discrete pulses of dense white smoke consisting of particles of terephthalic acid by the pulsing action of a fast-acting three-way valve. The trajectories of the smoke pulses can be tracked by a video imaging system without intruding in the flow around in flight. Two methods of pulsing the smoke were examined. The simplest and safest approach is to simply divert the smoke between the two outlet ports on the valve; this approach should be particularly effective if it were desired to inject smoke at two locations during the same test event. The second approach involves closing off one of the outlet ports to momentarily block the flow. The second approach requires careful control of valve dwell times to avoid excessive pressure buildup within the cartridge container and does also increase the velocity of the smoke injected into the flow. The flow of the smoke has been blocked for periods ranging from 30 to 80 milliseconds, depending on the system volume and the length of time the valve is allowed to remain open between valve closings.

Warden, M. S., Sorensen, S. T., Macarthur, J., Silver, M., Holtom, T. C., McDonald, C., Clive, P. J. M. and Bookey, H. T.

"DEVELOPMENT AND TESTING OF A TRIPLE-BEAM DOPPLER LIDAR SYSTEM FOR 3D WIND MEASUREMENT"

19th Coherent Laser Radar Conference (CLRC), Paper Tu6, June 2018, Okinawa, Japan.

We present results from our recent development of a triple-beam Doppler lidar system for accurate 3-dimensional wind measurements. The eye-safe all-fiber system consists of a central unit and three spatially separated remote units. The central unit contains a single seed laser that is shared between the remote unit. Each remote unit has its own optical amplifier, Risley prism beam steerer, and heterodyne detector. The photodiode signals are digitized and analyzed in the central unit. The three lidar emitters were verified against each other and a calibrated meteorological mast at Myres Hill near Glasgow. To test the converging beam methodology, the three remote units were arranged in an equilateral triangle with an 8 m distance from each to the central unit and the three beams were brought to intersect at a height of 60 m. Steps towards wind turbine blade integration will be outlined.

Ware, R., Carpenter, R., Guldner, J., Liljegren, J., Nehrkorn, T., Solheim, F. and Vandenberghe, F.

"A MULTICHANNEL RADIOMETRIC PROFILER OF TEMPERATURE, HUMIDITY, AND CLOUD LIQUID"

Radio Science, Vol. 38, No. 4, July 2003, pp. 44-1 - 44-12.

A microwave radiometer is described that provides continuous thermodynamic (temperature, water vapor, and moisture) soundings during clear and cloudy conditions. The radiometric profiler observes radiation intensity at 12 microwave frequencies, along with zenith infrared and surface meteorological measurements. Historical radiosonde and neural network or regression methods are used for profile retrieval. We compare radiometric, radiosonde, and forecast soundings and evaluate the accuracy of radiometric temperature and water vapor soundings based on statistical comparison with radiosonde soundings. We find that radiometric soundings are equivalent in accuracy to radiosonde soundings when used in numerical weather forecasting. A case study is described that demonstrates improved fog forecasting based on variational assimilation of radiometric soundings. The accuracy of radiometric cloud liquid soundings is evaluated by comparison with cloud liquid sensors carried by radiosondes. Accurate high-resolution three-dimensional water vapor and wind analysis is described based on assimilation of simulated thermodynamic and wind soundings along with GPS slant delays. Examples of mobile thermodynamics and wind profilers are shown. Thermodynamic profiling, particularly when combined with wind profiling and slant GPS, provides continuous atmospheric soundings for improved weather and dispersion forecasting.

Warne, J.

"PERFORMANCE VERIFICATION OF VAISALA ANEMOMETERS"

Instrument Test Report 676, September 2003, Commonwealth Bureau of Meteorology, Melbourne, Australia.

As part of a larger study of anemometers, a Vaisala WAA151 [S/N S45504] and a Vaisala WAA251 (S/N 803408) anemometer were tested to determine whether they met the Bureau of Meteorology Specification for accuracy and functionality. The WAA251 anemometer was installed over the winter of 1998 at Mt Hotham while the WAA151 anemometer was a new unit.

Wasileski, B. J.

"A STATE-SPACE FREE-VORTEX HYBRID WAKE MODEL FOR HELICOPTER ROTORS"

D.Sc. Thesis, June 2006, Washington University, St. Louis, MO.

This paper presents the development of a new hybrid wake model merging two distinctly different modeling approaches into a single, more comprehensive solution. The objective of the work was to leverage the strengths of each individual wake model creating a more flexible and extensible solution that could be used across the entire flight envelope of a helicopter. The results of the work indicate that the two wake models can be successfully merged. The results also show that hybrid wake provides a mechanism by which finite-state wake imparts a level of stability on the free wake solution allowing the free wake to provide consistent, repeatable results from hover through high-speed forward flight. While the new hybrid wake includes the geometric distortion needed for predicting the off-axis control response, the new model, as configured in this work, shows no sign of improvement in this area.

Wassaf, H. S.

"WAKE LOCALIZATION ENHANCEMENT VIA GEOMETRIC MEAN RECOMBINATION OF MULTI-SUBBAND ACOUSTIC IMAGES"

PhD Thesis, 2009, University of Massachusetts, Lowell, MA.

Airplane-generated wing tip wake vortices have been the subject of investigation and research by the FAA and NASA since the early 1970s. Their impact on airport safety and capacity has prompted more than thirty years of research and tens of millions of dollars. An integral part to the advancement of wake vortex research is the development of sensors capable of detecting and tracking wake vortices. In particular, passive acoustic based wake sensors such as microphone arrays have recently attracted attention. Advantages of such a sensor include remote sensing capability (unlike other surface wind measuring equipment such as sonic and propeller anemometers), capability to produce a 2-D smoke-like visualization of wakes, as well as potential capability to operate under fog and light rain when the performance of laser-based remote sensors are hampered. Wake hazard depends on many factors including wake strength, wake shape, as well as size and encountering geometry of the following aircraft relative to the wake of another aircraft. Therefore, improvements in acoustic imaging that lead to improvements in wake detection, localization, and the ability to resolve the shape of the core filament can help in quantifying the wake hazard. In this thesis, we devise a novel technique based on geometric mean of narrowband beamformed images to enhance wake detection, localization, and 2-D resolution of each wake filament. We introduce a localization and smoothing algorithm that transforms the enhanced images into two-dimensional wake positions. A wavelet packet extension of the

proposed geometric mean technique that gives greater control over the size and number of subbands is also presented. Finally, the effects of augmenting the proposed approach with an image deconvolution technique are evaluated. The advantages of the geometric mean approach are evaluated through a combination of analytical statistical analysis, simulations, and processing of real data. Throughout this evaluation, new metrics are defined and used to quantify the advantages of the new technique over the conventional time domain beamforming technique. It is also worthy to note that this newly devised approach can have applications beyond wake for imaging of broadband sources and is particularly effective when there is strong narrow band interfering sources.

Wassaf, H. S. and Wang, F. Y.

"DUALITY OF CIRCULATION DECAY STATISTICS AND SURVIVAL PROBABILITY"

AIAA Paper No. 2010-7990, August 2010, Toronto, Canada.

Survival probability and circulation decay history have both been used for setting wake turbulence separation standards. Conceptually a strong correlation should exist between these two characterizations of the vortex behavior, however, the literature lacks a rigorous development in establishing this correlation. The objective of this current paper is to establish the clear linkage between survival probability and circulation decay, and illustrate how they can be mapped to one another depending on need. The impact of the study is twofold. Firstly, it provides a means to infer circulation decay probabilistic bounds from survival probability curves, which is particularly useful in providing insight on circulation statistics at old wake ages where direct circulation measurements are often challenging. This is referred to as the reverse process. Second, in analyses that require survival probability such as encounter probability analysis, this survival probability can be inferred from known statistical decay curves. This will be referred to as the forward process.

Wassaf, H. S., Burnham, D. C. and Wang, F. Y.

"WAKE VORTEX TANGENTIAL VELOCITY ADAPTIVE SPECTRAL (TVAS) ALGORITHM FOR PULSED LIDAR SYSTEMS"

16th Coherent Laser Radar Conference, Long Beach, CA, June 2011.

Doppler Lidars have proven to be a major enabling technology for measuring aircraft wake vortices and effecting safety and capacity changes over the past decades. To date, the Lockheed Martin Coherent Technologies matched-filter software is the only commercially available pulsed Lidar wake vortex processing package and has provided the bulk of the wake data used by the FAA and EUROCONTROL to change wake separation rules. In 2008 the FAA tasked the Volpe Center with the development of a government owned processing package capable of performing wake detection, characterization and tracking. The current paper presents the background, progress, and capabilities to date on the Volpe Center developed Tangential Velocity Adaptive Spectral (TVAS) wake processing

package. The TVAS wake processing package is comprised of four major components: detection, localization, circulation estimation and Kalman filter based automated tracking.

Wassaf, H. S., Burnham, D. C. and Wang, F. Y.

"DIRECT MEASUREMENT OF INITIAL WAKE SEPARATION AND INITIAL CIRCULATION USING PULSED LIDARS"

17th Coherent Lidar Conference, June 2013, Barcelona, Spain.

A new direct approach to measuring the separation between two airplane wake vortices using the mean wind measurements from a short pulse lidar in an upward looking RHI configuration was presented. The simulation analysis showed that initial circulation can also be accurately measured after applying a correction factor. The correction factor was calculated as a function of look angle to the vortex pair center and varies from 1.33 to 1.36 for the angles of interest. The simulation shows that there are no significant biases in the b-zero measurement. The uncertainty analysis performed shows that 92 measurements per airplane type and configuration are approximately needed to meet the required uncertainty bounds of 2 percent for both circulation and b-zero measurement uncertainties. The future work will focus on the analysis of real measurement data and use it to build airplane specific circulation decay curves.

Wassaf, H. S., Burnham, D. C. and Wang, F. Y.

"WAKE VORTEX TANGENTIAL VELOCITY ADAPTIVE SPECTRAL (TVAS) ALGORITHM FOR PULSED LIDAR SYSTEMS"

16th Coherent Laser Conference, June 2011, Long Beach, CA.

The TVAS processing package for the tracking and characterization of wake vortices using pulsed Doppler lidar systems was presented. The published DLR algorithms for localization and circulation estimation formed the starting point for this development. The enhancements provided by TVAS in the areas of spectral modeling, localization and circulation estimations were described. Finally, simulation and field data validation of TVAS were presented. The simulation results showed that the hybrid algorithm is significantly less biased than the DLR FT algorithm at low circulations and produces a better match relative to the known input circulation values. In the case of field data, the differences between the TVAS and LMCT results were on the order of the self-consistency within each algorithm and are therefore not very significant. Although the discrepancy is not believed to be important in certain applications of the data, the sources of differences will be the subject of future studies. A KF tracker based on wake vortex dynamics is undergoing tuning and validation for the purpose of full automation of the processing, and will be presented in future publications.

Wassaf, H. S., Ibe, O. C., Dougherty, R. P. and Zhang, Y.

"ACOUSTICAL SPECTRAL ANALYSIS OF A WAKE VORTEX CROSS-SECTION USING MICROPHONE-ARRAYS"

149th Acoustical Soc. of America Meeting, Vancouver, Canada, May 2005

The ability to unambiguously identify the acoustic energy generated by airplane wake vortices using phased microphone-array intensity distribution maps is hampered by the lack of knowledge of the associated non-stationary spectrum throughout the wake's duration. This ambiguity is especially pronounced when the low broadband signal to noise ratio renders the wake signal difficult to isolate from contaminating background noise. In this paper, a technique to isolate the acoustic spectral content of a cross-sectional wake track (CSWT) is presented. First, image processing is used to generate a CSWT from vertical intensity distribution maps. In a second beamforming stage, the array's main-lobe traces the track to amplify the acoustic signal along the CSWT and estimate its time-varying Power Spectral Density (PSD) using Short Time Fourier Transform. Simultaneously, the time-varying upper confidence limit curve on the PSD of the background noise is also estimated at each time increment by steering the array away from the wake source. The time-varying upper confidence limit is then used as an adaptive threshold function on the estimate of the PSD in order to dynamically identify the wake frequency bands from those of the contaminating noise sources.

Wassaf, H. S., Tabrizi, A., Wang, F. Y. and Soares, M.

"ATMOSPHERIC TURBULENCE EFFECTS ON NEAR-GROUND WAKE VORTEX DEMISE"

88th AMS Annual Meeting, New Orleans, LA, January 2008

Departure wake vortex and atmospheric turbulence data collected from George Bush Intercontinental Houston Airport have been used to examine the relationship between eddy dissipation rate and wake demise near the ground. The analysis is made from the perspectives of the downwind vortex circulation decay as well as breakup dependence on wind and EDR. It is shown that a decrease of wake age with increasing wind magnitude and EDR is most likely due to an earlier onset of Crow instability as opposed to vortex decaying into background turbulence levels. However, it is worthy to note that most of the non-dimensional EDR values available in this study are considered low to moderate. So it is possible that more significant acceleration of the decay might be observed under higher EDRs. This will be further examined as more data from various airport sites become available.

Wassaf, H. S., Zhang, Y. and Ibe, O. C.

"WAKE ACOUSTIC ANALYSIS AND IMAGE DECOMPOSITION VIA BEAMFORMING OF MICROPHONE SIGNAL PROJECTIONS ON WAVELET SUBSPACES"

AIAA Paper No. 2006-2536, Cambridge, MA, May 2006

This paper describes the integration of wavelet analysis and time-domain beamforming of microphone array output signals for analyzing the acoustic emissions from airplane generated wake vortices. This integrated process provides visual and quantitative simultaneous information about the wake signal composition and array resolution for a particular wavelet subspace during a time interval.

In the results section, an example is given on how image processing algorithms might be used to automate the extraction of this information and select the wavelet subspaces from which to perform image reconstruction. This process begins with the projection of all the microphone signals on wavelet multi-resolution subspaces. The projections of these signals on the same wavelet subspace or scale are then beamformed to produce an image of the wake corresponding to that scale. Therefore, for each time interval, the process produces several images equal to that of the wavelet scales. This is equivalent to a more conventional Fourier-based idea of filtering the microphone signals with band-pass filters having non-uniform bandwidths then beamform in different sub-bands, but offers greater flexibility and enhanced computational speed. Results from both approaches will be shown, which ultimately illustrate the advantages of wavelet analysis over that of the Fourier-based analysis. Amongst the advantages are the speed of the decomposition and ease of the image reconstruction from selected subspaces aided by the perfect reconstruction and orthogonality properties of wavelet analysis.

Wassaf, H., Hardin, J. C. and Wang, F. Y.

"ATMOSPHERIC EFFECTS ON MICROPHONE ARRAY ANALYSIS OF AIRCRAFT VORTEX SOUND"

AIAA Paper No. 2006-2539, Cambridge, MA, May 2006.

This paper provides the basis of a comprehensive analysis of vortex sound propagation through the atmosphere to assess real atmospheric effects on acoustic array processing. Such effects may impact vortex localization accuracy and detection probability over longer distances. The paper shows that propagation through the atmosphere can significantly alter the propagation time of the rays from the source to the receiver from that which would be experienced in an ambient atmosphere. More importantly, it can also change the delay time between microphones on which the array processing is based. Implications of these results on the design and resolution of microphone arrays are discussed.

Watanabe, S. and Kato, H.

"STEREO PIV APPLICATIONS TO LARGE-SCALE LOW-SPEED WIND TUNNELS"

AIAA Paper No. 2003-0919, Reno, NV, January 2003

A stereo digital PIV technique is applied to some practical flowfields in large-scale low-speed wind tunnels in National Aerospace Laboratory of Japan. Instantaneous three-component velocity vectors are measured by using a stereo PIV system consisting of a high-intensity Nd:YAG laser, two high-resolution CCD cameras, a commercial PIV software on a PC, a calibration target traverse system, etc. Also, average velocity and turbulent quantities are obtained based on ensembles of the instantaneous velocity data. The wind tunnel applications include a tip vortex generated from a rectangular wing, jet-engine exhaust/external flow interactions for transport-type airplane, helicopter blade-vortex interactions (BVI), and leeward flow of a cranked-arrow-type wing. The results indicate that the stereo PIV is suitable and effective to investigate practical, complex velocity fields, at least qualitatively, in the large-scale low-speed wind tunnels. Some comparisons of the PIV results with seven-hole probe results

show relatively good agreements, proving quantitative validity of the PIV measurements to some degree, while detailed evaluations of the measurement uncertainty still remain to be conducted.

Watnick, M.

"AIRCRAFT WAKE VORTEX HAZARD WARNING APPARATUS"

US Patent 5,724,040, March 1998

An apparatus for monitoring the position of objects in a space including a target supervisor, a location supervisor, and a hazard monitoring supervisor. The apparatus can detect and respond to a potential wake-vortex hazard condition. The tracking supervisor receives target data from a sensor, characterizes and tracks selected objects, and provides target outputs having features respective of the selected objects. The location supervisor characterizes and displays features in the space, and provides a location output having the aforementioned features. The hazard monitoring supervisor detects and responds to potential hazard conditions, and provides a notice of such conditions, responsive to the target outputs and the location output. A data logger selectively retains the target outputs, the location output, or both. The position monitoring apparatus has six modes: full operation, non-airport-surveillance-radar, isolation, set-up, adaptation, and simulation. The target supervisor receives data from an airborne surveillance radar, a secondary surveillance radar, a global-positioning-system-based sensor, a ground-based sensor, or an auxiliary sensor.

Watson III, R. M.

"APPLICATION OF THE DISCONTINUOUS GALERKIN METHOD TO WAKE VORTEX FLOWS"

MS Thesis, May 2015, Auburn University, Auburn, Alabama.

A code was developed that utilizes the discontinuous Galerkin method to solve the Euler equations while utilizing a modal artificial viscosity sensor developed by Klockner. The sensor was augmented for the purpose of this research so that it could be run more quickly as well as having a more robust adaptation to different problems and specifically for this research the vortex burst problem. The sensor had several flops reduced from its calculation using a different approach for creation of the modes. This new approach was based on multiplying through by the Vandermonde matrix built from a one dimensional system instead of a three dimensional system. This was done by taking the cube of nodes for a cell and multiplying it by slices of data. The sensor was then made more robust by changing the value by which baseline decay model was added to the modes. The baseline decay model is needed to remove white noise from being sensed upon. Both these changes were reflected in examinations of routine test problems involving the Sod shock tube and the Kelvin-Helmholtz phenomena. With test cases validating the improvements to the sensor, the approach was then used against an element of wake vortex flow to show the sensor's robustness. Through plotting the pressure, vorticity, and total kinetic energy the test case was validated against previous research.

Watson, J. P. and Neitzel, G. P.

"NUMERICAL EVALUATION OF A VORTEX-BREAKDOWN CRITERION"

Phys. Fluids, Vol. 8, No. 11, November 1996, pp. 3063-3071

Numerical experimentation is used to examine the onset of axisymmetric vortex breakdown in a completely closed, cylindrical environment. Modification of the boundary motion allows one to compute a state of incipient vortex breakdown. The numerically determined states are used to test a recently posed hypothesis for the occurrence of vortex breakdown.

Wauben, W. M. F.

"EXPERIENCES WITH SONIC WIND SENSORS IN OPERATIONAL CONDITIONS"

WMO Technical Conference of Meteorological and Environmental Instruments and Methods, October 2012, Brussels, Belgium.

Previous investigations indicate that sonic wind sensors can be considered for operational use. In 2008 KNMI selected a 2D sonic wind sensor and introduced sonics in the measurement network to get operational experience. The reason for the replacement of conventional cup anemometers and wind vanes by sonic wind sensors is economical. The sonics have been installed at ten locations throughout the Netherlands, which have been selected to give a wide variety of conditions. At all locations the sonic has been installed in parallel to the existing operational cup anemometer wind vane combination. The measurements of the sonics and the cup anemometers and wind vanes have been made available in the measurement network to facilitate the user evaluation. A total of fifteen sonics were in the field for periods of about 1/2 to 2 1/2 years. Wind tunnel tests have been performed to verify the absolute calibration of the sonics and to check any possible degradation of the sonics during the field deployment. Based on the experiences of the field evaluation, specifically the interference and the damage inflicted by birds and ageing of the sonics, KNMI decided not to replace the cup anemometer and wind vane of the measurement network with sonics at this moment.

Wauben, W. M. F.

"WIND TUNNEL AND FIELD TEST OF THREE 2D SONIC ANEMOMETERS"

Technical Report No. 296, September 2007, Royal Netherlands Meteorological Institute, De Bilt, The Netherlands.

Three 2D sonic anemometers (so-called sonics) have been selected by KNMI and have been subjected to tests to establish whether they are suitable for operational use. The three sonics are the Thies 2D, the Gill Windobserver 2 and the Vaisala WAS425. The sonics have been compared to the KNMI cup anemometer and wind vane that are used operationally. After some initial tests, during which all three sensors showed some problems, all sensors were upgraded and the tests commenced. Wind tunnel tests were performed for wind speeds up to 75 m/s. Overall, the agreement of all sensors is within the WMO requirements, although in detail all three sensors have strong and weak points. The field test

showed that all 3 sonics worked properly although the Thies showed some signs of wear and the Vaisala occasionally missed a measurement. Overall, the sonics agree very well with each other. The differences between the sonics and the conventional cup and vane are larger. The differences for the 10-minute averaged wind speed show a strong directional dependence that is probably related to surface roughness. The results also show a dependency on precipitation intensity. Overall, the sonics seem suitable for operational use, but the use of sonics instead of the conventional wind sensors requires the construction of transfer functions for the homogenization of the climatological measurements.

Weaver, E. A., Bilbro, J. W., Dunkin, J. A. and Jeffreys, H. B.

"LASER DOPPLER TECHNOLOGY APPLIED TO ATMOSPHERIC ENVIRONMENTAL OPERATING PROBLEMS"

Proceedings Aircraft Safety and Operating Problems, NASA, Washington, DC, 1976, pp. 287-302.

Carbon dioxide laser Doppler ground wind data were very favorably compared with data from standard anemometers. As a result of these measurements, two breadboard systems were developed for taking research data: a continuous wave velocimeter and a pulsed Doppler system. The scanning continuous wave laser Doppler velocimeter developed for detecting, tracking and measuring aircraft wake vortices was successfully tested at an airport where it located vortices to an accuracy of 3 meters at a range of 150 meters. The airborne pulsed laser Doppler system was developed to detect and measure clear air turbulence (CAT). This system was tested aboard an aircraft, but jet stream CAT was not encountered. However, low altitude turbulence in cumulus clouds near a mountain range was detected by the system and encountered by the aircraft at the predicted time.

Webber, C. P.

"TESTING WAKE VORTICES FOR FORMATION PERSONNEL AIRDROP"

AIAA Paper No. 2003-2164, Monterey, CA, May 2003.

Development of new or significantly modified airlifters since 1990 with the potential to conduct formation personnel airdrops has presented the flight test community with a new challenge. Determination of acceptable formation geometry while minimizing the risk of paratrooper-vortex interactions during low-altitude tactical deployments has required new test and analysis techniques. This need became apparent in the mid-1990's during developmental flight test of the C-17A Globemaster III cargo plane. The original goal was to use standard C-141 formation geometry during personnel airdrop. However, the stronger wake vortices of the C-17A increased the probability of paratroopers having interactions with wake vortices from C-17A aircraft farther forward in the formation. A technique for studying wake vortices of aircraft in formation was required. Previous wake vortex studies had focused on the airfield environment with respect to takeoff and landing intervals for various sizes of aircraft. The phenomenon had not been studied from the perspective of formation personnel airdrop. It became necessary to measure the strength and location of the wake vortices of several different types of airlifters and compare the results of the C-17A wake measurements against

them. Since no vortex strength or position versus in-trail distance data were available for the C-130 or the C-141B, these aircraft were tested to provide a baseline to establish C-17A airdrop formation geometry. A ground-based Light Detection and Ranging (LIDAR) apparatus was employed to measure the strength and track the position of the vortices. The C-17A flew an oval 'racetrack' pattern phased with a C-130 or C-141B aircraft for comparison. From the vortex data, relative comparisons of the various aircraft could be made regarding vortex characteristics. This resulted in the spacing for C-17As to conduct formation personnel airdrop with minimum risk of paratrooper/vortex encounters. When the C-130J was undergoing Qualification Test and Evaluation (QT&E), the same type of equipment and methodology was used to verify whether it could fly in the same formation geometry as earlier models of C-130 without increasing the risk of paratrooper/vortex encounters. This was a desire of the using command. The external differences of the C-130J compared to a C-130H are new propellers and engines and the lack of wing-mounted external fuel tanks. The two aircraft made numerous alternating passes by the Lidar equipment. The processed data were compared to determine whether the vortex characteristics of the two aircraft were measurably different, and if so, by what margin. Subsequently, the vortices of a C-130J-30 (fuselage extended 15 feet from a standard C-130J) were compared to those of a C-130H by the same method. This paper details the background, test and analysis methods, and conclusions of wake vortex studies at the Air Force Flight Test Center.

Webel, O. M. and Bearman, P. W.

"A TOWING TANK STUDY OF THE DYNAMICS OF TRAILING VORTICES IN VARIOUS CONFIGURATIONS"

AIAA Paper No. 2006-3750, San Francisco, CA, June 2006

A towing tank study is presented investigating the dynamics of two and three vortices in various configurations (orientation, vortex strength and separation). These vortices are generated by an array of rectangular planform wings at chord-based Reynolds number in the range 1,000 to 10,000. A Dye Flow Visualisation technique is applied to determine the qualitative behavior of the flow and to measure the wavelengths of occurring instabilities. Two-dimensional Particle Image Velocimetry measurements and subsequent postprocessing will provide a number of quantitative flow characteristics such as vortex circulation, vorticity fields and flow energy.

Weber, F.

"WAKE VORTEX TURBULENCE AND ITS EFFECT ON THE FLIGHT OPERATIONS -POSSIBILITIES FOR ITS EXPLORATION AND PREDICTION"

Ortung und Navigation, No. 3, 1977, pp. 77-85

It has been found that turbulence effects produced in the wake of a large aircraft can constitute a danger for other aircraft which are passing through the turbulent region. The danger is particularly great during takeoff and landing operations. A description is presented of the results of investigations which have been conducted in the U.S. and England to obtain information regarding the origin and the characteristics of wake turbulence. It was found that wake vortices are generated at the wing tip in the

form of a pair of vortices which consist of masses of air rotating in the opposite direction. The behavior of the wake vortices after their generation is discussed. Predicted and photographically observed vortex paths are shown in a graph. The nature of the hazards represented by the trailing vortices is examined and a description is provided of vortex tracking systems. Attention is also given to the time periods during which trailing vortices remain in a certain 'security zone' of the London-Heathrow Airport.

Weber, O. and Ulken, R.

"A THEORETICAL STUDY OF THE IMPACT OF AIRCRAFT WAKE VORTICES ON ROOFS IN THE FINAL APPROACH AREA OF DUSSELDORF AIRPORT"

DFVLR-MITT-82-01, December 1981, DFVLR, Braunschweig, Germany.

Damage to buildings caused by the impact of trailing wake vortices shed from wide-bodied aircraft in the final approach area of Dusseldorf Airport was studied. Forty-two occurrences of roof damage were analyzed, using a simplified model for the strength, transport, and decay of wake vortices. The model is interpreted with reference to the results of a vortex alleviation program carried out in the U.S. Wake vortex characteristics, maximum tangential velocity and vortex decay are discussed. Measurement of vortex far field reduction is considered. Other investigations of roof damage in the approach areas of Hamburg, Berlin (Tempelhof), and London (Heathrow) airports are summarized. The value of potential aircraft modifications and precautions on the ground are assessed, suggesting supplementary measurements on board aircraft and in buildings. [In German.]

Webster, C. A. G.

"AN EXPERIMENTAL STUDY OF TURBULENCE IN A DENSITY-STRATIFIED SHEAR FLOW"

Journal of Fluid Mechanics, Vol. 19, Issue 2, June 1964, pp. 221-245.

This paper concerns an investigation of turbulence in the density stratified shear flow of a specially designed wind tunnel in which the density gradient is created by differential heating of the air. The first three sections of the paper consist of a description of the apparatus and of the mean temperature and velocity gradients in the tunnel, together with a discussion of a method of measuring low wind speeds based on the periodic shedding of vortices by a circular cylinder. In the remaining sections details of the experimentally determined structure of the turbulence of the flow and of its eddy conductivity and viscosity are presented and their dependence on the over-all gradient form of Richardson number considered.

Wedemeyer, E.

"VORTEX BREAKDOWN"

AGARD-VKI Lecture Series 121 on High Angle of Attack Aerodynamics, Rhode Saint Genese, Belgium, March 1982

The different forms of vortex breakdown are considered. Experimental results, theoretical explanations, and predictions are discussed with emphasis on vortex breakdown over wings with highly swept leading edges.

Wedemeyer, E. H.

"STABLE AND UNSTABLE VORTEX SEPARATION"

Fluid Dynamics Panel Symposium, AGARD-CP-247, October 1978, pp. 13-1--13-10.

A theoretical study of the stability of leading-edge separation on delta wings is presented. The theory explains the change from steady vortex type separation which is observed for highly swept wings to flow with unsteady 'separation bubble' which is typical for wings of small sweepback. Calculations show, that solutions of the vortex-sheet model of leading-edge separation can become unstable if the angle of attack is sufficiently high. The critical angle of attack beyond which no stable solutions exist, decreases with decreasing sweepback angle. The calculated stability boundary is in good agreement with the boundary for observed leading edge vortices. These findings suggest, that the change from 'vortex type' to 'bubble type' separation is due to the change from stable to unstable leading-edge vortices. Finally, the theory explains the effect of a strake on a wing of moderate sweep and aspect ratio: The strong leading-edge vortices generated by the strake induce an outboard flow on the main wing and thereby increase the effective sweep of the leading edge. The higher effective sweep stabilizes the leading-edge separation on the main wing.

Weger, J. and Chokani, N.

"EXPERIMENTAL DESIGN OF A SUPERSONIC SHOCK WAVE/VORTEX INTERACTION AT MACH 3"

ASME Forum on Turbulent Flows, Vol. 112, June 1991, pp. 17-22.

Research was conducted to develop an experimental design for the qualitative and quantitative investigation of a supersonic shock wave/vortex interaction. This interaction is of importance in the design and performance analysis of supersonic combustors. The research involved flow field verification of the North Carolina State University Supersonic Wind Tunnel Facility, test model design, schlieren door design, and experimental verification of the model design. The test design, mounting of shock wave and vortex generators upon a flat plate, provides the capability to investigate the oblique shock wave/vortex interaction. Considerations were given to both optical (non-intrusive) and pitot probe (intrusive) data acquisition. Design features include the minimization of interaction interference from shock and expansion waves emanating off the test section models, prevention of tunnel blockage, and the minimization of any three-dimensional effects. Test results indicate a successful design, as the interaction was achieved. Recommendations for continued research in this area and planned modifications to the test design are included.

Wei, Z., Li, Z., Liu, F. and Liu, W.

"METHODS OF AIRCRAFT RE-CATEGORIZATIONS FOR REDUCING WAKE VORTEX SEPARATIONS"

12th USA/Europe Air Traffic Management Research and Development Seminar (ATM2017), June 2017, Seattle, WA.

The current criteria of wake vortex separation may limit the capacity of the busy airports despite ensuring flight safety. Based on plenty of measured data together with the knowledge of wake vortex behavior, the concept of Re-categorization (RECAT) has been proposed by the international air traffic researchers. This concept has attracted more and more interests, as it can apply to reduce separations with more precision by increasing the number of aircraft categories. The methods for classifying aircraft categories were studied systematically, and the parameters termed as Required Decay Distance (RDD) and Wake Vortex Impedance (WVI) were proposed by authors to consider the influence of leading aircraft's wake vortex circulation, and the resistant ability of following aircraft when encountering wake vortex. By comparing RECAT-I with RECAT-EU, the standard we proposed called RECAT-NEW can obtain more balanced and reasonable results in safety domain. Furthermore, based on the data in airport peak operation conditions, the RECAT-NEW is expected to increase 2.2 percent of airport capacity.

Weigand, A. and Gharib, M.

"ON THE EVOLUTION OF LAMINAR VORTEX RINGS"

Experiments in Fluids, Vol. 22, 1997, pp. 447-457

Using Laser Doppler Anemometry (LDA) and Digital Particle Image Velocimetry (DPIV), the physical properties of laminar vortex rings are investigated in the Reynolds-number range of 830-1650. The measured initial circulations of the vortex rings are found to agree well with corrected versions of the vorticity-flux (slug-flow) model proposed by Didden and Pullin. The DPIV and LDA data show excellent agreement regarding local velocities and vortex-ring circulations. The DPIV data depict the distribution of the vorticity and circulation in the core regions, where the resulting vorticity distributions are found to be self-similar Gaussian profiles. The propagation velocity of the vortex rings is well approximated by an analytical model of Saffman for large core sizes. In the asymptotic limit, the trajectories are in excellent agreement with the exact Stokes-dipole solution of Cantwell and Rott.

Wells, J.

"EFFECTS OF TURBULENCE MODELING ON RANS SIMULATIONS OF TIP VORTICES"

MS Thesis, August 2009, Virginia Polytechnic Institute and State University, Blacksburg, VA.

The primary purpose of this thesis is to quantify the effects of RANS turbulence modeling on the resolution of free shear flows. The simulation of aerodynamic wing-tip vortices is used as a test bed.

The primary configuration is flow over an isolated finite wing with aspect ratio 8.66 and Reynolds number 530000. Tip-vortex velocity profiles, vortex core and wake turbulence levels, and Reynolds stresses are compared with wind tunnel measurements. Three turbulence models for RANS closure are tested: the Lumley, Reece, and Rodi full Reynolds stress transport model and the Spalart-Allmaras model with and without a proposed modification. The main finding is that simulations with the full Reynolds stress transport model show remarkable mean flow agreement in the vortex and wake due to the proper prediction of a laminar vortex core. Simulations with the Spalart-Allmaras model did not indicate a laminar core and predicted over-diffusion of the tip-vortex.

Wen, C. Y., Wu, W. J. and Chen, H.

"SHOCK-VORTEX INTERACTIONS IN A SOAP FILM"

Shock Waves, Vol. 18, 2008, pp. 185-191

This work experimentally visualizes the interaction of a quasi-one-dimensional moving shock wave with a two-dimensional vortex in a soap film for the first time. A vertical soap film shock tube was used to generate a quasi-one-dimensional moving shock wave and a NACA-0012 airfoil intruded into the soap film was towed to shed the starting vortex. The interesting interaction phenomena were then visualized using a traditional high-speed flash photography. The concentration of sodium dodecyl sulfate (SDS) used was 0.5 CMC (critical micelle concentration) to keep the surfactant molecules behave as two-dimensional gases. A sequence of pictures shows that the shock is distorted non-symmetrically as it passes through the spiral vortex flow field and the vortex structure is compressed in the direction normal to the shock. These flow features observed in soap films are qualitatively similar to their counterparts in gases. In addition, the visualization of the interactions of a quasi-one-dimensional moving shock wave with a Karman vortex street are presented.

Wendt, B. J.

"PARAMETRIC STUDY OF VORTICES SHED FROM AIRFOIL VORTEX GENERATORS"

AIAA Journal, Vol. 42, No. 11, November 2004, pp. 2185-2195.

Extensive parametric study of vortices shed from the tips of airfoil vortex generators has been conducted to determine the dependence of initial vortex circulation and peak vorticity on elements of airfoil geometry and impinging-flow conditions. The vortex generators were symmetric airfoils examined in subsonic airflow on the surface of a straight pipe. The circulation and peak-vorticity data were derived from cross-plane velocity measurements acquired with a seven-hole probe one chord length downstream of the airfoil-trailing-edge-tip location. Circulation and peak vorticity are observed to be proportional to the freestream Mach number, the angle of attack, and the span-to-boundary-layer-thickness ratio. Unlike circulation, which decreases in monotonic fashion with increasing airfoil aspect ratio, peak vorticity is observed to increase with increasing aspect ratio, reaching a maximum before falling off at higher values. The circulation may be accurately modeled with an expression based on Prandtl's relationship between finite airfoil circulation and airfoil geometry. A correlation for the

peak vorticity has been derived from a conservation relationship equating the moment at the airfoil tip to the rate of angular-momentum production of the shed vortex, modeled as a Lamb (ideal viscous) vortex, and is shown to provide excellent qualitative agreement with the observed behavior of peak vorticity.

Wendt, B. J.

"INITIAL PEAK VORTICITY BEHAVIOR FOR VORTICES SHED FROM AIRFOIL VORTEX GENERATORS"

AIAA Paper No. 1998-0693, Reno, NV, January 1998

Simple 2D models of a vortex are constructed to mimic a vortex newly shed from an airfoil vortex generator. The model vortices have Oseen-like properties, and are constructed in terms of circulation and peak vorticity. The models are integrated for cross plane angular momentum, and an expression based on Prandtl's relationship between finite airfoil circulation and airfoil geometry is substituted for vortex circulation. Using a conservation relationship, peak velocity of the shed vortex is then isolated in terms of vortex generator geometry. Results indicate a good comparison to data taken on low aspect ratio airfoil vortex generators. The influence of the wall is studied using a patchwork model vortex patterned after the Rankine vortex. The wall is modeled by superimposing an image vortex. Both the analysis and the data indicate that the presence of the wall depresses the magnitude of peak vorticity for the lowest values of aspect ratio and span-to-boundary layer thickness ratio.

Wendt, B. J. and Reichert, B. A.

"SPANWISE SPACING EFFECTS ON THE INITIAL STRUCTURE AND DECAY OF AXIAL VORTICES"

AIAA Paper No. 1996-2518, New Orleans, LA, June 1996

The initial structure and axial decay of an array of streamwise vortices embedded in a turbulent pipe boundary layer is experimentally investigated. The vortices are shed in counter-rotating fashion from an array of equally-spaced symmetric airfoil vortex generators. Vortex structure is quantified in terms of cross plane circulation and peak streamwise vorticity. Flow conditions are subsonic and incompressible. The focus of this study is on the effect of the initial spacing between the parent vortex generators. Arrays with vortex generators spaced at 15 and 30 degrees apart are considered. When the spacing between vortex generators is decreased the circulation and peak vorticity of the shed vortices increases. Analysis indicates these strengthening results are from regions of fluid acceleration in the vicinity of the vortex generator array. Decreased spacing between the constituent vortices also produces increased rates of circulation and peak vorticity decay.

Wenren, Y. and Steinhoff, J.

"APPLICATION OF VORTICITY CONFINEMENT TO THE PREDICITON OF THE WAKE OF HELICOPTOR ROTORS AND COMPLEX BODIES"

AIAA Paper No. 1999-3200, Norfolk, VA, June-July 1999.

A new method is described for computing high Reynolds number incompressible vortex dominated flows which is fundamentally different from conventional viscous CFD schemes. The method is completely Eulerian and can be used with regular Cartesian grids, yet it allows the computation of thin convecting vortices over arbitrarily long distances with no numerical spreading, which is inherent in Lagrangian methods but not possible in conventional Eulerian ones. Further, it automatically allows the general separation, linking and other types of interactions of vortical regions inherent in Eulerian methods but difficult with Lagrangian ones. The technique is also applied to thin boundary layers on solid surfaces with (non-conforming) Cartesian grids. The method is based on a technique - 'Vorticity Confinement' that effectively represents a new type of model for turbulent vortical regions. This model does not involve formulating model partial differential equations for these regions, which then must be discretized. Instead, difference equations are solved (in the vortical regions) which directly result in the desired vortical structure. After a basic description, an application is given for the computation of wake flow for a rotor in hover. This is followed by computations of separating flow over rotorcraft fuselages and, finally, an entire helicopter in forward flight, including rotor, wake, and fuselage.

Wentz, Jr., W. H., Ostowari, C. and Seetharam, H. C.

"EFFECTS OF DESIGN VARIABLES ON SPOILER CONTROL EFFECTIVENESS, HINGE MOMENTS, AND WAKE TURBULENCE"

AIAA Paper No. 1981-0072, St. Louis, MO, January 198.

Wind tunnel tests have been conducted to determine effects of certain design variables on spoiler performance and spoiler flow field characteristics. Measurements include forces and surface pressures, oil flow surveys on a vertical splitter plate, wake pressures, and wake velocity and turbulence measurements using a dual split-film anemometer system. Results include the effects of spoiler design variables, such as: spoiler slope for constant projection height, hingeline gap, lower surface venting and deflector, spoiler trailing edge notching and spoiler porosity. Hingeline gap, porosity, lower surface venting and lower surface deflector can be designed to reduce control dead-band tendency. Wake turbulence studies show that certain modifications can be utilized to diminish peak frequencies in the wake.

Werle, H.

"ON VORTEX BURSTING"

NASA TM-77587, June 1984, Washington, DC.

The phenomena of vortex bursting has been pointed out for the first time in 1960, in 'La Recherche Aeronautique'; since then, it has been the subject of many theoretical and experimental papers. Now it is studied mostly by means of visualization. In this manner, the physical behavior of the phenomenon is emphasized, and its similarity with boundary layer separation or wake bursting becomes apparent. The essential influence of an increasing pressure gradient on the initiation, the position and the type of

bursting is clearly confirmed. Lastly, the evolution of the phenomena as a function of several parameters is analyzed in the case of delta wings, alone or installed on aircraft models; and compared with the results of similar wind tunnel or flight tests.

Werle, H.

"VORTEX INTERACTIONS OF FIXED AND OSCILLATING DELTA WINGS (WATER TUNNEL VISUALIZATIONS)"

La Recherche Aerospatiale, No. 1989-2, January 1989, pp. 43-68.

Vortex interactions around a wide variety of models with delta wings have been visualized in a series of water tunnel tests at ONERA. The effects can be either beneficial (delaying a stall or vortex breakdown) or harmful (critical configurations that are difficult to control). The present article reviews a few typical examples that were observed, first in steady regime around stationary models (wings with or without canard, full aircraft with or without canard, missiles) and then in unsteady mode around models driven in harmonic oscillatory pitching motion. In many cases, visualization of the near wakes of the tested models are also provided.

Werle, H. and Fiant, C.

"WATER-TUNNEL VISUALIZATION OF THE FLOW AROUND THE MODEL OF A 'CONCORDE' TYPE AIRPLANE"

La Recherche Aerospatiale, No. 102, September-October 1964, pp. 3-19.

Tests at the water-tunnel opened the way to the qualitative study of the flow around a model of a simplified 'Concorde' type airplane in the landing configuration. They have shown the structure, the location and the bursting of the upper surface vortices, the evolution of these elements versus the flow parameters, the shape and the configuration, the turbojet exhaust induction on the flow and the ground effect (with a fixed plate and with an endless belt simulating the ground). Many pictures are included. [In French.]

Werner, C.

"FAST SECTOR SCAN AND PATTERN RECOGNITION FOR A CW LASER DOPPLER ANEMOMETER"

Applied Optics, Vol. 24, November 1985, pp. 3557-3564.

A fast data system was developed for a CW laser Doppler anemometer. Using a digital differentiation technique, it allows multiple peak values in a Doppler spectrum to be recorded at 50-msec intervals. Computer programs for sine wave fitting of the data for a velocity-azimuth-display (VAD) scan pattern or a reduced sector VAD scan are used to reduce the errors in the wind field determination in unfavorable weather conditions. The sector scan is necessary if the field of view is limited by buildings etc., and the time consumption for a sector scan is much less than the full VAD scan. For atmospheric inhomogeneities such as wake vortex signatures, a special pattern recognition procedure was

developed. This procedure identifies inhomogeneities in the stored velocity information, and the result can be used to draw the wake vortex distribution in time or range.

Werner, C., Flamant, P. H., Reitebuch, O., Kopp, F., Streicher, J., Rahm, S., Nagel, E., Klier, M., Herrmann, H., Loth, C., Delville, P., Drobinski, P., Romand, B., Boitel, C., Oh, D., Lopez, M., Meissonnier, M., Bruneau, D. and Dabas, A.

"WIND INFRARED DOPPLER LIDAR INSTRUMENT"

Optical Engineering, Vol. 40, No. 1, January 2001, pp. 115-125.

The purpose of the project WIND (wind infrared Doppler lidar) is the development of an airborne conical scanning CO₂ Doppler lidar in French-German cooperation by CNRS/CNES and DLR. The instrument and its peculiarities are described. Measurements of the Doppler shift from a moving platform with an accuracy of 1 m/s require instantaneous access to the position data of the platform. Therefore, this part of the instrument is described in detail. Ground-based tests, airborne tests and a validation flight were performed. The instrument can be used for mesoscale meteorology to test models and contribute to a spaceborne Doppler lidar in the future.

Werner, C., Kopp, F., Schwiesow, R. and Bachstein, F.

"METHOD FOR DETERMINING THE DIRECTION AND SPEED OF WIND IN THE ATMOSPHERE"

US Patent 4,735,503, April 1988.

A method and device is provided for determining the direction and speed of wind in the atmosphere by means of a laser-Doppler anemometer, wherein only values measured in a sector of about 100 degrees and less of an azimuth scan are supplied or fed to a multiple-peak finder of a measuring device. To eliminate the influences from clouds, haze, fog and the like in the measuring device, several frequency maximums are always traced in the multiple-peak finder, whereby in each case a preceding maximum is related to a trailing maximum until the trailing maximum is smaller than the preceding maximum. Because of the attainable high-speed sector scanning, the measuring device can be used for the determination of multiple wind peaks caused by clouds and/or fog echoes, or at an installation site where the measuring range is highly restricted, or also for detecting aircraft wake vortices.

Wernert, P., Koerber, G. and Wietrich, F.

"NEW EXPERIMENTAL APPARATUS FOR THE STUDY OF THE UNSTEADY FLOWFIELD OVER AN AIRFOIL IN PITCHING AND HEAVING MOTIONS USING LASER DOPPLER ANEMOMETRY"

ETN-94-95126, October 1992, Institut Franco-Allemand de Recherches, Saint-Louis, France.

An experimental setup used for the study of the flowfield over an airfoil undergoing arbitrary pitching or heaving motions is described. This setup is basically composed of two parts: a novel driving mechanism, based on an automatic apparatus, two speed drives, two brushless motors and a support

system, which allows the airfoil to be put into a wide range of periodic or transient motions and a classical two-dimensional laser Doppler anemometry system which provides streamwise and transversal components of the velocity. Data acquisition, data reduction and synchronization problems are discussed. Results concerning dynamic stall features observed in the near wake of a pitching airfoil at a Reynolds number of 287,000 are given.

West, L., Gimmestad, G., Herkert, R., Smith, W. L., Kireev, S., Schaffner, P. R., Daniels, T. S., Cornman, L. B., Sharman, R., Weakley, A., Perram, G., Gross, K., Smith, G., Feltz, W., Taylor, J. and Olson, E.

"HAZARD DETECTION ANALYSIS FOR A FORWARD-LOOKING INTERFEROMETER"

NASA TP 2010-216845, August 2010, Langley Research Center, Hampton, VA.

The Forward-Looking Interferometer (FLI) is a new instrument concept for obtaining the measurements required to alert flight crews to potential weather hazards to safe flight. To meet the needs of the commercial fleet, such a sensor should address multiple hazards to warrant the costs of development, certification, installation, training, and maintenance. The FLI concept is based on high-resolution Infrared Fourier Transform Spectrometry (FTS) technologies that have been developed for satellite remote sensing. These technologies have also been applied to the detection of aerosols and gases for other purposes. The FLI concept is being evaluated for its potential to address multiple hazards including clear air turbulence (CAT), volcanic ash, wake vortices, low slant range visibility, dry wind shear, and icing during all phases of flight (takeoff, cruise, and landing). The research accomplished in this second phase of the FLI project was in three major areas: further sensitivity studies to better understand the potential capabilities and requirements for an airborne FLI instrument, field measurements that were conducted to provide empirical demonstrations of radiometric hazard detection, and theoretical work to support the development of algorithms to determine the severity of detected hazards. With respect to wake vortices, the report documented a series of simulation and analyses of flight test experiences. It appears that there is no convincing evidence wake signatures had been found in these trials.

West, L., Gimmestad, G., Lane, S., Smith, B. L., Kireev, S., Daniels, T. S., Cornman, L. and Sharman, B.

"AIRBORNE FORWARD-LOOKING INTERFEROMETER FOR THE DETECTION OF TERMINAL-AREA HAZARDS"

NASA CR 2014-218167, February 2014, NASA Langley Research Center, Hampton, VA.

The Forward-Looking Interferometer (FLI) program was a multi-year cooperative research effort to investigate the use of imaging radiometers with high spectral resolution, using both modeling/simulation and field experiments, along with sophisticated data analysis techniques that were originally developed for analysis of data from space-based radiometers and hyperspectral imagers. This investigation has advanced the state of knowledge in this technical area, and the FLI program developed a greatly improved understanding of the radiometric signal strength of aviation hazards in a wide range of scenarios, in addition to a much better understanding of the real-world

functionality requirements for hazard detection instruments. The project conducted field experiments on three hazards (turbulence, runway conditions, and wake vortices) and analytical studies on several others including volcanic ash, reduced visibility conditions, in flight icing conditions, and volcanic ash.

West, L., Gimmestad, G., Smith, W., Kireev, S., Cornman, L. B., Schaffner, P. R. and Tsoucalas, G.

"APPLICATIONS OF A FORWARD-LOOKING INTERFEROMETER FOR THE ON-BOARD DETECTION OF AVIATION WEATHER HAZARDS"

NASA/TP-2008-215536, October 2008, Langley Research Center, Hampton, VA

The Forward-Looking Interferometer (FLI) is a new instrument concept for obtaining measurements of potential weather hazards to alert flight crews. The FLI concept is based on high-resolution Infrared (IR) Fourier Transform Spectrometry (FTS) technologies that have been developed for satellite remote sensing, and which have also been applied to the detection of aerosols and gasses for other purposes. It is being evaluated for multiple hazards including clear air turbulence, volcanic ash, wake vortices, low slant range visibility, dry wind shear, and icing, during all phases of flight.

Weston, R. P., Liu, C. H. and Ting, L.

"NUMERICAL STUDIES OF THE MERGING OF VORTICES"

AIAA Paper No. 1986-0557, Reno, NV, January 1986

A newly improved method has been employed to study the roll-up and decay of trailing vortex sheets. This method is obtained by using a scheme formulated recently Liu et al., September 1985 to improve the accuracy of the boundary data. The scheme is much more efficient than the previous one used by Weston and Liu (1982). Comparisons of the present numerical results with other numerical solutions of the Navier-Stokes equations are presented.

Westwater, F. L.

"ROLLING UP OF THE SURFACE OF DISCONTINUITY BEHIND AN AEROFOIL OF FINITE SPAN"

R&M 1692, August 1935, Aeronautical Research Council, Great Britain

The existence of a surface of discontinuity or vortex sheet behind an airfoil of finite span is well known. In aero-dynamic problems it is necessary to calculate the interference flow due to the vortices of this sheet. The vortex sheet is unstable and rolls up, the rolling up beginning at the edges. The paper discusses the rolling up process in detail.

Wetmore, J. W.

"AIRCRAFT TRAILING VORTICES - A HAZARD TO OPERATIONS"

Aeronautics and Astronautics, Vol. 2, No. 12, December 1964, pp. 44-51.

It is shown how a thorough understanding of the phenomenon of aircraft trailing vortices, coupled with air-traffic procedures emphasizing appropriate sequencing and flight-path control, can help prevent an increase in incidents as the volume of air traffic grows. The characteristics of vortices are reviewed and expected load factors which could develop on aircraft which inadvertently penetrate a vortex are shown.

Wetmore, J. W. and Reeder, J. P.

"AIRCRAFT VORTEX WAKES IN RELATION TO TERMINAL OPERATIONS"

NASA TN D-1777, April 1963, NASA Langley Research Center, Hampton, VA.

An analysis has been made, based on present understanding of trailing vortex characteristics, to provide an indication of the possible effects on aircraft encountering these vortices, the circumstances under which encounters might occur in terminal-area operations, and some means of dealing with the vortex problem in operations planning and traffic control.

Wetmore, J. W. and Reeder, J. P.

"AIRCRAFT VORTEX WAKES IN RELATION TO TERMINAL OPERATIONS"

NASA TM-X-51683, November 1962, NASA Langley Research Center, Langley Station, VA

The purpose of this paper is to examine the problems associated with trailing vortices, particularly in the airport terminal area where separation of aircraft must be kept to a safe minimum for efficient traffic handling and where the low flight speeds result in more intense vortices. A brief discussion is given of the formation of trailing vortices from lifting surfaces and of the effects of such major factors as aircraft weight, wingspan, and speed on intensity and extent of the resulting airflow disturbance. The decay of vortex intensity with time is considered in the light of available experimental results and theory. Effects on aircraft encountering trailing vortices including structural loads, upset, and settling are considered together with the influencing factors. Finally, the theoretically determined timewise settling and spreading of the trailing vortices from an airplane in typical takeoff and landing are described and discussed in relation to safe procedures for following airplanes. Airplanes considered as examples in the discussion include a heavy jet transport of 300,000 lb gross weight, a 35,000 lb light turboprop transport and a 2,000 lb light personal airplane.

Wetzel, B. E. and Pfyl, F. A.

"MEASUREMENTS OF DOWNWASH AND SIDEWASH BEHIND CRUCIFORM TRIANGULAR WINGS AT MACH NUMBER 1.4"

NACA-RM-A51B20, April 1951, Ames Aeronautical Lab., Moffett Field, CA.

The results of an experimental investigation of the downwash and sidewash flow angles in a transverse plane behind a cruciform-wing and body combination are presented. The wing-body combination was composed of a cruciform arrangement of two identical triangular wings of aspect ratio 2.31 corresponding to a leading-edge sweep angle of 60 degrees, placed on a body of fineness ratio of 16. The investigation was conducted at a Mach number of 1.40 and at a Reynolds number of 1.25 million based on the mean aerodynamic chord of the wings. Downwash and sidewash measurements were made for angles of bank of 0, 11.25, 22.5, and 45 degrees and through an angle-of-attack range of + and -8 degrees.

Whitcomb, R. T.

"A DESIGN APPROACH AND SELECTED WIND TUNNEL RESULTS AT HIGH SUBSONIC SPEEDS FOR WING-TIP MOUNTED WINGLETS"

NASA TN D-8260, July 1976, NASA Langley Research Center, Hampton, VA.

Winglets, which are small, nearly vertical, winglike surfaces, substantially reduce drag coefficients at lifting conditions. The primary winglet surfaces are rearward above the wing tips; secondary surfaces are forward below the wing tips. This report presents a discussion of the considerations involved in the design of the winglets; measured effects of these surfaces on the aerodynamic forces, moments, and loads for a representative first-generation, narrow-body jet transport wing; and a comparison of these effects with those for a wing-tip extension which results in approximately the same increase in bending moment at the wing-fuselage juncture as did the addition of the winglets.

White, Jr., R. P.

"VORTEX DISSIPATOR"

US Patent 3,845,918, November 1974

A vortex dissipator for the tip of an airfoil or hydrofoil lifting surface is formed as a fixed plate secured to the tip and aligned with the free stream direction. The plate extends forward from the trailing edge of the tip and outward from the suction side of the lifting surface and is configured so that the resultant of the velocity of the free stream flow and the rotational velocity of the vortex produces a stall angle of attack relative to the plate and dissipates much of the strength of the vortex.

White, Jr., R. P. and Balcerak, J. C.

"THE NEMESIS OF THE TRAILED TIP VORTEX - IS IT NOW CONQUERED?"

28th Annual National V/STOL Forum, American Helicopter Society, Washington, DC, May 1972

A recent experimental research program was conducted by the authors in which the outer section of an UH-1D helicopter blade was modified to incorporate a system for injecting the tip vortex produced by the blade with a mass of linearly-directed air. The effects of nozzle geometry, the velocity of

injection, the turbulence wavelength, and the angle of injection on the resulting strength of the trailed tip vortex are presented in terms of quantitative measurements of the circulation strength as a function of the injected mass of air. Data obtained from flow-visualization studies in which illuminated helium bubbles, smoke, and tuft grids were used are also presented. Comparisons are made with results of associated research investigations previously conducted by the authors, and with results of similar research efforts conducted by other investigators.

White, Jr., R. P., Gangwani, S. T. and Janakiram, D. S.

"A THEORETICAL AND EXPERIMENTAL INVESTIGATION OF VORTEX FLOW CONTROL FOR HIGH LIFT GENERATION"

RASA/SRL-14-78-1, March 1978, Systems Research Labs., Newport News, VA.

An experimental and theoretical program of research was conducted to determine the effect of the main wing wake on the effectiveness of the horizontal tail surface and to further refine and expand the predictive theory initiated during the previous years' effort. Experimentally, it was determined that while the vortex flows developed large pitching moments on the wing, the horizontal tail surface, regardless of its geometrical location with respect to the wing MAC, was able to counter the pitching moment and trim the configuration. The experimental data also indicated that, while large changes in the pitch angle of the horizontal tail were required to obtain configuration trim when the concentrated wing vortex wake was in the vicinity of the horizontal tail surface, the aerodynamic angle of attack remained relatively small and the tail effectiveness did not change by more than 25%. The refined and expanded theoretical prediction method provided greater insight in the aerodynamic characteristics on the upper and lower surface and, in general, predicted the vortex flow effects more accurately. The results suggest that with the proper program streamlining and documentation the predictive program can be used successfully as a design tool.

White, R. J.

"EFFECT OF WIND SHEAR ON AIRSPEED DURING AIRPLANE LANDING APPROACH"

J. Aircraft, Vol. 29, No. 2, March-April 1992, pp. 237-242

Equations are presented for calculating the gust velocity along the landing flight path of an airplane due to the presence of wind shear. Based on this gust input data, airplane equations of motion are solved to determine the minimum airspeed developed during trimmed flight along the landing flight path. Using the developed gust equations, it is shown that the use of a tilted vortex pair provides an improved agreement with measured wind shear velocities. Here, a longitudinal velocity ratio is defined along with a selected vortex core radius. The nonlinear gust velocities are then approximated by a broken line linear ramp gust to use as input gust data for the airplane equations of motion. From this, the minimum airspeed is found along with the flight-path position.

Whitehead, E. J.

"THE STABILITY OF MULTIPLE WING-TIP VORTICES"

PhD Thesis, July 2009, University of Adelaide, Adelaide, South Australia.

Over the last forty or so years interest in the study of wing-tip vortices has increased, primarily due to the introduction of larger passenger aircraft and their subsequent interaction with smaller aircraft. The vortices generated by these larger aircraft present a problem in two main areas: the wake hazard problem, where other aircraft can be subjected to the large tangential velocities of the vortex, and the interaction with ground-based features of vortices created during landing and take-off. The first of these is particularly dangerous close to the ground when aircraft are in a high lift configuration at take-off and landing. As the vortices effectively scale with aircraft wing span, significant encounters between large vortices and smaller aircraft have been documented over the years. An example of one such documented wake vortex interaction incident can be found in Ogawa. In this study, the system of vortices are described as classical Batchelor vortices (or linear superpositions thereof) which are then subjected to small perturbations. By discretizing the domain and solving for the eigenvalues of the system it is possible to ascertain the stability characteristics of the flow as a function of the system parameters which include the axial wave-number, the spacing of the vortices, their cross-flow decay rate and their axial strength. We first consider the inviscid instability of multiple tip vortices, an approximation which is valid in the limit of large Reynolds numbers. In this limit the stability of the flow is dominated by the axial component of the basic vortex flow. The governing equations of continuity and momentum are reduced to a second order partial differential equation (PDE). This equation is solved numerically to determine which vortex configurations produce the greatest instability growth rate. These results are extended to consider the effect of compressibility on the inviscid instability. Finally, we consider the effects of viscosity on the stability of the full Batchelor similarity solution which results in a second order PDE in four dependent variables. The stability equations are solved both globally (for the entire eigenspectra) and locally (for a single eigenvalue in a pre-determined region) using codes that run in both serial and parallel form. The numerical methods are based on pseudo-spectral discretization (Chebyshev polynomials for Cartesian and radial directions and Fourier for azimuthal) in the global scheme, the eigenvalues being recovered either with a QZ algorithm or a shift-and-invert Arnoldi algorithm. For the local scheme, fourth order centered finite-differences are used in conjunction with an iterative eigenvalue recovery method.

Whitehouse, G. R. and Brown, R. E.

"HELICOPTER ROTOR RESPONSE TO WAKE ENCOUNTERS IN GROUND EFFECT"

59th Forum, American Helicopter Society, Phoenix, AZ, May 2003

Interactions between helicopters and aircraft wakes are most likely to occur near airports, especially during takeoff and landing. Under these conditions, helicopter flight is characterized by low forward speeds and the presence of ground effect. Recent studies conducted out of ground effect have suggested that, particularly at low speeds, the mutually-induced deformation of both the rotor wake and the wake of the aircraft with which it is interacting may be an important factor in limiting the thrust

and flapping response of the helicopter during a wake encounter. Numerical prediction of helicopter performance in ground effect remains a challenge, however. In particular, certain experimentally observed features of the rotor flow, such as the formation of the characteristic 'ground vortex' and the dynamics of its interaction with the remainder of the rotor flow field, require extremely long-term calculations to capture. In this paper, the development of the rotor flow field in ground effect is studied using a CFD-based approach which, through its vorticity conserving properties, is ideally suited to capturing vortical features in the flow that take many rotor revolutions to develop. Preliminary calculations of the rotor's response to interactions with an aircraft's wake in ground effect are then presented. The rotor's response to a wake interaction in ground effect appears to be more severe than its response in free air, principally because the presence of the ground plane restricts the mutually-induced deformation of the wakes of the helicopter and the interacting aircraft.

Whitehouse, G. R. and Brown, R. E.

"MODELLING A HELICOPTER ROTOR'S RESPONSE TO WAKE ENCOUNTERS"

Aeronautical Journal, January 2004, pp. 15-26.

In recent years, various strategies for the concurrent operation of fixed- and rotary-wing aircraft have been proposed as a means of increasing airport capacity. Some of these strategies will increase the likelihood of encounters with the wakes of aircraft operating nearby. Several studies now exist where numerical simulations have been used to assess the impact of encounters with the wakes of large transport aircraft on the safety of helicopter operations under such conditions. This paper contrasts the predictions of several commonly-used numerical simulation techniques when each is used to model the dynamics of a helicopter rotor during the same idealized wake encounter. In most previous studies the mutually-induced distortion of the wakes of the rotor and the interacting aircraft has been neglected, yielding the so-called 'frozen vortex' assumption. This assumption is shown to be valid only when the helicopter encounters the aircraft wake at high forward speed. At the low forward speeds most relevant to near-airfield operations, however, injudicious use of the frozen vortex assumption may lead to significant errors in predicting the severity of a helicopter's response to a wake encounter.

Whitehouse, G. R. and Brown, R. E.

"MODELING THE MUTUAL DISTORTIONS OF INTERACTING HELICOPTER AND AIRCRAFT WAKES"

Journal of Aircraft, Vol. 40, No. 3, May-June 2003, pp. 440-449

Flight procedures that will decrease the following distance between successive aircraft have been considered as a means of alleviating pressures on airport capacity while still conforming to conventional air traffic management rules. A major limitation to the implementation of such procedures is perceived to be an associated increase in the possible severity of encounters with the wakes of nearby aircraft. Modeling efforts have focused on quantifying such interactions in terms of structural loading or degradation in handling and have established that helicopters respond in a fundamentally different way than fixed-wing aircraft to encounters with wake vortices. This paper

suggests that, particularly at the low forward speeds typical of terminal phase operations, the mutually induced distortion of the helicopter's own wake and the wake of the interacting aircraft strongly influences the aerodynamics of the helicopter rotor. Results from numerical simulations suggest that neglecting this aspect of the interaction, as has commonly been done in the past, can indeed be valid at high helicopter forward speeds, but can lead to significant misrepresentation of the severity of wake encounters under terminal flight conditions.

Whitehouse, G. R., Wachspress, D. A. and Quackenbush, T. R.

"AERODYNAMIC DESIGN OF HELICOPTER ROTORS FOR REDUCED BROWNOUT"

International Powered Lift Conference, American Helicopter Society, October 2010, Philadelphia, PA.

Rotorcraft brownout is caused by the entrainment of dust and ground debris by the rotor wash during takeoff and landing, and is a critical operational problem. Brownout affects safe operations due to the reduction of visibility, in addition to damaging engine components and rotor blades. Recent experience gained from operations in brownout with a variety of rotorcraft configurations, dynamically scaled test facilities as well as ongoing work with validated analyses at Continuum Dynamics, Inc., indicates that aerodynamic modifications to the aircraft may offer a complementary approach to sensor-based brownout solutions. This paper reviews the underlying brownout flow-physics, with particular emphasis on the critical connection between wake dynamics and tip vortex properties, and the development of a strategy to best exploit fluid-dynamic mechanisms to reduce brownout without adversely affecting the aerodynamic performance of the rotor system. Emphasis will be placed on explaining why basic rotor scaling parameters have little influence on brownout and why AW101/EH101/US101, and the Sea King with advanced blades, might offer improved brownout performance. Practical methods are presented for implementing modifications in a retrofittable manner that do not degrade the aerodynamic performance of the helicopter and are commensurate with current procurement systems.

Whitelaw, J. H.

"CONFERENCE ON CAPACITY AND WAKE VORTICES HELD IN IMPERIAL COLLEGE OF SCIENCE, LONDON ON 11-14 SEPTEMBER 2001"

USGRDR0209, September 2001, Imperial College of Science and Technology, London, England

Reports the effects of swirling turbulence caused by jets taking off and landing on planes in Singapore. Creation of disruptive swirling vortex; Formation of wake vortices; Importance of rollers in the stopping of swirling vortex.

Whitford, R.

"DESIGN OF AN ULTRA-HIGH CAPACITY AIRCRAFT"

AIAA and SAE, World Aviation Conference, September 1998

Recent forecasts have been that airline passenger traffic will almost triple by the year 2015 even if growth is less than the air transport industry's average of 5.5 percent over the last 20 years. This will lead to further increases in ATC system and airport congestion, forcing airlines to use larger aircraft than hitherto. Design teams on both sides of the Atlantic are working on concepts for ultrahigh capacity airliners (UHCAs) to satisfy the anticipated need. However, larger aircraft present major problems: taxiway and runway width limits, gate limits, passenger handling, emergency evacuation, community noise, and aircraft separation due to wake vortices. Several different feasibility studies (occupying approximately 1,500 manhours each) have been carried out at the Royal Military College of Science into the design of UHCAs of broadly classical design. Each of the designs has been aimed at providing 600-700 triclass seat/1000 economy seat transport aircraft. The topics of configuration, passenger cabin layout, and size constraints are addressed.

Wickens, R. H.

"WAKE VORTEX TRAJECTORIES OF LOW FLYING SPRAY AIRCRAFT"

Canadian Aeronautics and Space Journal, Vol. 26, No. 1, First Quarter 1980, pp. 41-45

Under stable atmospheric conditions with no wind, the spray cloud descends to the forest canopy under the combined effects of gravity, and the aircraft vortex wake which, during the initial stage of formation, has a great influence on the configuration and dimensions of the emission. In fact, the motion of droplets smaller than 100 microns in diameter conforms almost completely to the classical patterns of vortex flow, rotating around the trailing vortices. In such conditions, the vortex cores and their entrained droplets are visible and still coherent at tree level, and the spray deposition will have a lateral dimension not too different from the aircraft span.

Wickens, R. H.

"THE AERODYNAMIC CHARACTERISTICS AND TRAILING VORTEX WAKE OF PROPELLER V/STOL CONFIGURATIONS"

Canadian Aeronautics and Space Journal, Vol. 21, No. 3, March 1975, pp. 81-98

This paper describes the aerodynamic characteristics of lifting propellers and wing-propeller configurations, with particular reference to the concept of a powered-lift system, and its complex flows downstream in the wake. The propeller, when inclined to large angles, and at high advance ratios, is a singular example of a powered-lift system in which lift is derived partly by deflecting and energizing a stream tube of air, and, in part, by a wing-like vortex flow in which the propeller disc can be thought of as a low aspect ratio wing of circular plan form. The trailing wake is characterized by mixed regions of propulsive and vortex flow in which concentrations of vorticity may induce downwash and sidewash velocities of considerable magnitude in the surrounding fluid. The propulsive stream tube, or slipstream, is an integral part of this wake, and deforms with it, ultimately rolling up with the trailing vortices.

Wickens, R. M.

"THE VORTEX WAKE AND AERODYNAMIC LOAD DISTRIBUTION OF SLENDER RECTANGULAR WINGS"

Canadian Aeronautics and Space Journal, Vol. 13, June 1967, pp. 247-260

An experimental investigation has been made of the aerodynamic characteristics of two slender rectangular plates or wings having an aspect ratio of 1/4. One of the plates was flat, the other had a midchord deflection of 20 deg. The flow on the upper surface of both plates was characterized by a pair of rolled up vortex sheets, which spring from the streamwise edge and are similar to those shed from slender, sharp-edged delta wings. The secondary vortices, which are frequently seen on deltas, however, were not observed (for zero yaw) at any incidence.

Wickens, R. M.

"THE TRAILING VORTEX WAKE DOWNWIND OF AN EXTERNAL FLOW JET FLAP"

Canadian Aero. and Space Journal, Vol. 18, No. 3, March 1972, pp. 67-68

A five-hole probe was used to map out the flow behind a wing containing both propulsive and vortical components. The rolled-up vortices which characterize the trailing jet sheet were observed by smoke flow visualization, but strong vorticity was evident in the relative orientation of the side-wash and downwash contours.

Wickens, R. M.

"A TECHNIQUE FOR SIMULATING THE MOTION AND GROUND EFFECT OF AIRCRAFT WAKE VORTICES"

Canadian Aero. and Space J., Vol. 26, 1980, pp. 129-133

An experimental technique is described which is intended to simulate the motion and induced flows of a vortex pair in ground effect without the use of a wind tunnel or lifting surface. The basic principle of the simulation is that the trailing vortex flows which occur in planes downwind of the aircraft, relative to an observer fixed on the ground, are similar in most respects to the vortex pair in two-dimensional flows. The production of lift and the shedding of trailing vortices result from a large number of short impulsive flows which disturb the ambient fluid and merge into a continuous streamwise effect. The sudden appearance of the vortices and their subsequent downward motion is meant to represent the passage of an aircraft above an observer on the ground.

Widnall, S. E.

"A CORRELATION OF VORTEX NOISE DATA FROM HELICOPTER MAIN ROTORS"

Journal of Aircraft, Vol. 6, No. 3, May-June 1969, pp. 179-281.

The present and future use of helicopters as flexible air transportation in and out of highly restricted heavily populated areas is threatened by the community noise problems associated with these vehicles. In the next generation of vehicles, noise requirements may play a major role in the design process. It is important to have in the early stages of the design process an estimate for the effect of a given design change upon both the noise and DOC of the vehicle. This Note presents a correlation of existing data on main rotor noise which is, at the present state-of-the-art, an irreducible effect of operating the main rotor. Although basic research into the effect of airfoil cross-section and tip planform shape on the noise from main rotors may eventually lead to noise reductions below this curve, an examination of the present data can also serve as a base to compare later improvements.

Widnall, S. E.

"THE STABILITY OF A HELICAL VORTEX FILAMENT"

J. Fluid Mech., Vol. 54, Part 4, March 1972, pp. 641-663

The stability of a helical vortex filament of finite core and infinite extent to small sinusoidal displacements of its center-line is considered. The influence of the entire perturbed filament on the self-induced motion of each element is taken into account. The effect of the details of the vorticity distribution within the finite vortex core on the self-induced motion due to the bending of its axis is calculated using the results obtained previously by Widnall, Bliss & Zelay. In this previous work, an application of the method of matched asymptotic expansions resulted in a general solution for the self-induced motion resulting from the bending of a slender vortex filament with an arbitrary distribution of vorticity and axial velocity within the core. The results of the stability calculations presented in this paper show that the helical vortex filament has three modes of instability; a very short-wave instability which probably exists on all curved filaments, a long-wave mode which is also found to be unstable by the local-induction model and a mutual-inductance mode which appears as the pitch of the helix decreases and the neighboring turns of the filament begin to interact strongly. Increasing the vortex core size is found to reduce the amplification rate of the long-wave instability, to increase the amplification rate of the mutual-inductance instability and to decrease the wavenumber of the short-wave instability.

Widnall, S. E.

"THE STRUCTURE AND DYNAMICS OF VORTEX FILAMENTS"

Annual Review of Fluid Mechanics, Vol. 7, Annual Reviews Inc., Palo Alto, CA, 1975, pp. 141-165

A review is given of the fluid mechanics of trailing vortices and vortex rings as well as in the more general problem of the structure, motion, and stability of free vortices: compact regions of concentrated vorticity in free motion in a surrounding fluid that is either homogeneous and at rest or with weak background vorticity or stratification.

Widnall, S. E. and Bliss, D. B.

"SELF-INDUCED MOTION AND STABILITY OF CONCENTRATED VORTEX FILAMENTS"

Archives of Mechanics (Archiwum Mechaniki Stosowanej), Vol. 26, No. 3, 1974, pp. 459-478.

The self-induced motion and stability of vortex filaments has been investigated both theoretically and experimentally. Through an application of the method of matched asymptotic expansions, a general solution is obtained for the self-induced motion of a vortex filament containing an arbitrary distribution of swirl and possibly axial velocities. This solution has been applied to several vortex-flow stability problems: the stability of a vortex line containing an axial jet, the mutual inductance instability of a vortex pair and the instability of helical vortex filaments and vortex rings. Only the results for the vortex ring will be discussed in detail. Experimental studies of a vortex ring using a Laser Doppler Velocimeter were performed to determine the circulation and vorticity distribution within the vortex rings. Comparison of the observed vortex-ring motion and instability with theoretical predictions will be presented.

Widnall, S. E. and Bliss, D. B.

"SLENDER-BODY ANALYSIS OF THE MOTION AND STABILITY OF A VORTEX CONTAINING AN AXIAL FLOW"

J. Fluid Mech., Vol. 50, Part 2, November 1971, pp. 335-353

Previous results concerning the effects of axial velocity on the motion of vortex filaments are reviewed. These results suggest that slender-body force balance between the Kutta-Joukowski lift on the vortex cross-section and the momentum flux within the curved filament will give some insight into the behavior of the filament. These simple ideas are exploited for both a single vortex filament and a vortex pair, both containing axial flow. The stability of a straight vortex filament containing an axial flow to long wave sinusoidal displacements of its center-line is investigated and the stability boundary obtained. The effect of axial flow on the stability of a vortex pair is explored. It is shown that to lowest order (in the ratio of vortex core radius to distance between the vortices) the effect of axial flow is to reduce the self-induced rotation of a single filament and that this effect can be considered as a change in effective core radius. To the next order, travelling waves appear in the instability, the instability mode for the vortex pair becomes non-planar but the amplification rate of the instability is not affected.

Widnall, S. E., Bliss, D. B. and Tsai, C. Y.

"THE INSTABILITY OF SHORT WAVES ON A VORTEX RING"

J. Fluid Mech., Vol. 66, Part 1, 1974, pp. 35-47.

A simple model for the experimentally observed instability of the vortex ring to azimuthal bending waves of wavelength comparable with the core size is presented. Short-wave instabilities are discussed for both the vortex ring and the vortex pair. Instability for both the ring and the pair is predicted to occur whenever the self-induced rotation of waves on the filament passes through zero. Although this

does not occur for the first radial bending mode of a vortex filament, it is shown to be possible for bending modes with a more complex radial structure with at least one node at some radius within the core.

Widnall, S. E., Bliss, D. B. and Zalay, A. D.

"THEORETICAL AND EXPERIMENTAL STUDY OF THE STABILITY OF A VORTEX PAIR"

Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, pp. 305-338

The linear stability of the trailing vortex pair from an aircraft is discussed. The method of matched asymptotic expansions is used to obtain a general solution for the flow field within and near a curved vortex filament with an arbitrary distribution of swirl and axial velocities. The velocity field induced near the vortex core by distant portions of the vortex line is calculated for a sinusoidally perturbed vortex filament and for a vortex ring. General expressions for the self-induced motion are given for these two cases. It is shown that the details of the vorticity and axial velocity distributions affect the self-induced motion only through the kinetic energy of the swirl and the axial momentum flux. The presence of axial velocity in the core reduces both the angular velocity of the sinusoidal vortex filament and the speed of the ring. Experimental results for the distortion and breakup of a perturbed vortex pair are presented.

Wie, S. Y., Im, D. K., Kwon, J. H. and Lee, D. J.

"NUMERICAL SIMULATION OF ROTOR USING COUPLED COMPUTATIONAL FLUID DYNAMICS AND FREE WAKE"

Journal of Aircraft, Vol. 47, No. 4, July-August 2010, pp. 1167-1177.

Rotor aerodynamics is governed by wake behavior. Particularly, aerodynamic performance in the hovering flight condition is determined by the structure and the strength of the wake. In this paper, rotating blades were simulated using a tightly coupled computational fluid dynamics and time-marching free-wake method in hovering and forward flight. The rotating blades and a flowfield near the rotor are calculated by computational fluid dynamics, and the strength and motions of the wake are simulated with the time-marching free-wake method. A moving overset grid technique is applied to consider rotor motions during hovering and forward flight. Inflow and outflow conditions in the computational fluid dynamics domain are provided from an induced flow rate by the time-marching free-wake method at each time step. The strength of the trailed vortices is determined from a sectional lift calculated in the rotating blade, which is computed using the computational fluid dynamics. The present coupled method was compared with other inflow and outflow conditions, such as source-sink and Riemann-invariant conditions. To investigate the robustness of the present method, grid-size effects were also tested in large and small background grid systems.

Wie, S. Y., Lee, S. and Lee, D. J.

"POTENTIAL PANEL AND TIME-MARCHING FREE-WAKE COUPLING ANALYSIS FOR HELICOPTER ROTOR"

Journal of Aircraft, Vol. 46, No. 3, May-June 2009, pp. 1030-1041.

A potential-based panel method coupled with advanced time-marching free-wake techniques is developed to achieve fast and accurate prediction for unsteady aerodynamics and wake dynamics of helicopter rotating blades. This coupling analysis is enabled by using the equivalence of the doublet-wake panels and the vortex filaments. The coupled panel method allows the inclusion of the self-induced velocity of curved vortex filaments and high-order time integration for the computation of wake convection. A parallel computation is applied to the wake convection for fast numerical calculation. The computation of the induced velocity from each vortex filament is parallelized and computed separately. The velocity-field integration technique is used to avoid numerical singularity during the interaction between the wake and blades. It is found that blade-pressure predictions and the wake roll-up agree well with the measured data for helicopter rotors, both in hover and forward flight. Tip-vortex pairing phenomena are also predicted and compared with the measured data.

Wiegele, A., Rahm, S. and Smalikho, I.

"GROUND-BASED AND AIR-BORNE LIDAR FOR WAKE VORTEX DETECTION AND CHARACTERISATION"

1st CEAS European Air and Space Conference, Berlin, Germany, September 2007, pp. 1055-1059

In the last two years several ground-based and airborne wake vortex campaigns have been performed with the DLR coherent Doppler Lidar. The objectives of those campaigns were (i) measurements for comparison with the wake vortex prediction and monitoring system WSVBS, (ii) the measurement and description of wakes generated by the new Airbus A380 aircraft and a reference aircraft for the ICAO landing separation, and (iii) the observation of the influence of different configurations on the vortex life time in the project AWIATOR.

Wilczak, J., Benjamin, S., Djalalova, I., Bianco, L., Freedman, J., Finley, C., Orwig, K., Clawson, K., Coulter, R. and Cline, J.

"ENHANCING SHORT TERM WIND ENERGY FORECASTING WITH REMOTE SENSING: THE WIND FORECAST IMPROVEMENT PROJECT (WFIP)"

9th International Symposium on Tropospheric Profiling (ISTP), September 2012, University of L'Aquila, L'Aquila, Italy.

It is widely recognized within the wind energy and electric utility operations communities that current skill levels of wind energy forecasting are adding increased costs to the integration of wind energy onto the U.S. electrical grid. To address this, the U.S. Department of Energy has implemented a joint research program with NOAA and private industry to improve wind energy forecasts. The key elements of this program are 1) a one-year deployment of extensive meteorological observing systems in two regions with significant wind energy production; 2) assimilation of these observations into research models; and 3) evaluation of the benefits of these improved wind forecasts on electrical utility operations, especially for ramp-events in the 0-6 h forecast time-frame.

Wild, J.

"WAKE PREDICTION AND MODELING IMPROVEMENT OF AN EXISTING MODEL"

MS Thesis, April 2014, double degree with ISAE Supaero, Toulouse, France, and KTH Royal Institute of Technology, Stockholm, Sweden.

This thesis is dedicated to the study of atmospheric turbulence and its effects on wake-vortex decay. Wake-vortices are a by-product of the lift that makes every aircraft fly. Under certain special conditions, the decay-time of a wake-vortex can be high and thereby impose constraints on separation between aircraft. A precise knowledge of background turbulence will hence improve the ability of predicting the decay of a wake-vortex. To compute the turbulence, LIDAR measurements have been used to calculate an EDR value (Eddy Dissipation Rate) of the air mass of interest. This parameter indeed quantifies the background turbulence and is of importance in the decay model. The results of this calculation will then be used to improve an overall wake-vortex simulation tool developed by AVTECH. The work performed during this master thesis has established several improvements in the wake-vortex decay model developed by AVTECH thanks to the input of the LIDAR data.

Wilk, L. S.

"BACKSCATTER DATA ANALYSIS"

MIT-MSL-RE-88, August 1973, MIT Measurement Systems Lab., Cambridge, MA

This report presents the results of data analysis performed on data acquired from a previous test operation. That operation undertaken in September, October, and November 1972 at the Vortex Test Facility at the National Aviation Experimental Center, Pleasantville, N.J., involved the design, operation and data acquisition of a monostatic acoustic backscatter vortex detection sensor. This report briefly reviews the previous effort, describes the technique used to reduce the data, and draws conclusions from the analysis. The end results of the data processing - various types of acoustograms - are contained under separate cover and have not been reproduced. Those acoustograms from an integral part of this report. The conclusion drawn from this study is that it is possible to build a monostatic, acoustic backscatter vortex sensor, and that the next phase of development can be undertaken with a considerable degree of confidence that the technical feasibility of a backscatter sensor can be demonstrated.

Willert, C.

"STEREOSCOPIC DIGITAL PARTICLE IMAGE VELOCIMETRY FOR APPLICATION IN WIND TUNNEL FLOWS"

Measurement Science and Technology, Vol. 8, 1997, pp. 1465-1479.

A particle image velocimetry system capable of accurately recovering the out-of-plane velocity component has been realized based on a stereoscopic viewing arrangement. To allow a large viewing

angle with long focal length objective lenses, the angular displacement or Scheimpflug imaging configuration is employed in which the image, object and lens planes intersect in a common line. The varying magnification factor associated with this imaging configuration is accounted for using an accurate and simple-to-use calibration procedure based on solving the projection equations for each of the two cameras. A pair of high-resolution cameras, both capable of recording image pairs in the microsecond range, are synchronized to a pulsed Nd-YAG laser. By placing the cameras on either side of the light sheet the favorable light scattering characteristics of micron-sized seeding particles in forward scatter provide images at significantly higher illumination than at normal or backscatter viewing angles. Ultimately designed for use in industrial wind tunnels, the camera system can work with non-symmetric arrangements. It has been successfully tested in a laboratory environment by imaging the unsteady flow field of a vortex ring passing through a laser light sheet. Adaptive processing software capable of dynamically adjusting the sample location of the interrogation windows to the local displacement vector significantly improves data yield. The algorithm requires only the selection of the final window/overlap size. The hierarchical interrogation approach permits the processing of images whose displacement dynamic range exceeds the interrogation window size.

Willert, C., Stockhausen, G., Beversdorff, M., Klinner, J., Lempereur, C., Barricau, P., Quest, J. and Jansen, U.

"APPLICATION OF DOPPLER GLOBAL VELOCIMETRY IN CRYOGENIC WIND TUNNELS"

12th International Symposium on Applications of Laser Techniques in Fluid Mechanics Paper 25-3, Lisbon, Portugal, July 2004

A specially designed Doppler global velocimetry system (DGV, planar Doppler velocimetry) was developed and installed in a high-speed cryogenic wind tunnel facility for use at free stream Mach numbers between 0.2 and 0.88 and pressures between 1.2 and 3.3 bar. The necessary particle seeding was achieved by injecting a mixture of gaseous nitrogen and water vapor into the dry and cold tunnel flow which then immediately formed a large amount of small ice crystals. As operational and access conditions are very restrictive with respect to other facilities, DGV is currently considered the best choice for the non-intrusive measurement of flow fields. Three component velocity maps were achieved by simultaneously imaging a common area in the flow field from three different directions through the wind tunnel side walls by means of a multiple branch fiber imaging bundle attached to a common DGV image receiving system. The complete imaging system and fiber-fed light sheet generators were installed inside the generally inaccessible pressure plenum surrounding the wind tunnel's test section. The control PC and frequency-stabilized laser system, requiring occasional re-adjustment, were placed outside of the pressure shell. The DGV system acquired flow maps with an area of 300 x 300 mm (squared) in the wake of simple vortex generators as well as from a half-span aircraft model with different wing tip devices. While the remotely controlled hardware operated reliably over the course of three months, a variety of problems mainly relating to light reflections and icing on the observation windows significantly impaired the measurements. These problems could partially be resolved by covering the view background with dull black paint.

Willert, C., Stockhausen, G., Beversdorff, M., Klinner, J., Lempereur, C., Barricau, P., Quest, J. and Jansen, U.

"APPLICATION OF DOPPLER GLOBAL VELOCIMETRY IN CRYOGENIC WIND TUNNELS"

Experiments in Fluids, Vol. 39, 2005, pp. 420-430.

A specially designed Doppler global velocimetry system (DGV, planar Doppler velocimetry) was developed and installed in a high-speed cryogenic wind tunnel facility for use at free stream Mach numbers between 0.2 and 0.88, and pressures between 1.2 bar and 3.3 bar. Particle seeding was achieved by injecting a mixture of gaseous nitrogen and water vapor into the dry and cold tunnel flow, which then immediately formed a large amount of small ice crystals. Given the limited physical and optical access for this facility, DGV is considered the best choice for non-intrusive flow field measurements. A multiple branch fiber imaging bundle attached to a common DGV image receiving system simultaneously viewed a common area in the flow field from three different directions through the wind tunnel side walls. The complete imaging system and fiber-fed light sheet generators were installed inside the normally inaccessible pressure plenum surrounding the wind tunnel's test section. The system control and frequency-stabilized laser system were placed outside of the pressure shell. With a field of view of 300x300 square mm, the DGV system acquired flow maps at a spatial resolution of 3x3 square mm in the wake of simple vortex generators as well as in the wake of different wing-tip devices on a half-span aircraft model, although problems mainly relating to light reflections and icing on the observation windows significantly impaired part of the measurements, the remotely controlled hardware operated reliably over the course of three months.

Williams, D.

"MORE AIR TRAFFIC"

Aerospace International, Vol. 25, No. 5, May 1998, pp. 24-25

This article discusses how the UK's Defence Evaluation and Research Agency (DERA) is harnessing its expertise to the task of wake vortex measurements to improve safety at busy airports. The use of lidar for measurements of wake vortices and for more general atmospheric monitoring, for instance to measure the wind field surrounding an airport, is discussed.

Williams, D. and Lohr, G.

"WAKE TURBULENCE MITIGATION FOR ARRIVALS (WTMA)"

ICAS 2008, Anchorage, AK, Sept. 2008

The preliminary Wake Turbulence Mitigation for Arrivals (WTMA) concept of operations is described in this paper. The WTMA concept provides further detail to work initiated by the Wake Vortex Avoidance System Concept Evaluation Team and is an evolution of the Wake Turbulence Mitigation for Departure concept. Anticipated benefits about reducing wake turbulence separation standards in crosswind conditions, and candidate WTMA system considerations are discussed.

Williams, G. M.

"A TWO-DIMENSIONAL WAKE MODEL FOR THE VISCOUS TRAILING VORTEX PAIR FORMED
DOWNSTREAM OF A LIFTING WING"

LR-25070, February 1972, Lockheed-California Company, Burbank, CA

The trailing vortex wake system downstream of a lifting, finite wing is modeled with a pair of two-dimensional, laminar, viscous vortex models of the multi-vortex type. The initial, or 'embryonic' form of this viscous wake model is matched to the inviscid Betz model of the trailing vortex pair formed by the roll-up of the trailing-edge vortex sheet. Downstream profiles derived from the viscous wake model appear to agree well with limited results from published experimental data. The proposed wake model predicts that the wing span load distribution will have a strong influence on the character and aging processes of the downstream flow; some of these predictions have been qualitatively observed in published reports of flight test investigations.

Williams, G. M.

"VISCOUS MODELLING OF WING-GENERATED TRAILING VORTICES"

Aero. Quarterly, Vol. 25, May 1974, pp. 143-154

The trailing vortex wake system generated by a lifting wing of finite span is modeled with a pair of laminar, viscous vortex models of a new type. This embryonic form of the viscous wake model is matched, at several interior collocation points, to the viscous Betz model of the wake convolution process that transforms the wing trailing-edge vortex sheet into a pair of axisymmetric trailing vortices. The present laminar theory appears to offer a useful basis for developing an engineering prediction method of airplane wake characteristics.

Williams, G. M.

"TRAILING VORTEX WAKE SYSTEMS"

LR-24275, January 1971, Lockheed-California Company, Burbank, CA

The report is a general review of the aircraft wake turbulence problem. More emphasis is given to the aerodynamic aspects of the problem than is devoted to related areas such as operational avoidance procedures. The fundamental properties of vortices are discussed, and mathematical models of vortex formation and decay are developed.

Williams, J. E. F. and O'Shea, S.

"SOUND GENERATION BY HYDRODYNAMIC SOURCES NEAR A CAVITATED LINE VORTEX"

Journal of Fluid Mechanics, Vol. 43, part 4, 1970, pp. 675-688.

The paper examines the scattering properties of a cavitated line vortex when excited by line and point sources of sound. It is found that the vortex resonances discovered by Kelvin for incompressible flow are essentially unmodified by fluid compressibility, and that many of the resonant modes radiate energy to infinity. Those resonant modes dominate the vortex response, their amplitude growing algebraically with time in a driven instability of the model flow. The off-resonance response is dependent on the value of a normalized frequency parameter (w/Q) squared times.

Williams, J. K. and Meymaris, G.

"REMOTE TURBULENCE DETECTION USING GROUND-BASED DOPPLER WEATHER RADAR"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 7, 2016, Springer International Publishing Switzerland, pp. 149-178.

Turbulence in and around clouds can pose a significant hazard to aviation, with convective turbulence identified as being responsible for a majority of all turbulence-related aircraft accidents. Regions of convective turbulence may be small (about 1 km) and highly transient (about a few minutes). Graphical Turbulence Guidance, an operational NWP-based turbulence forecast, produces hourly forecasts at a relatively coarse spatial resolution and does not explicitly forecast convective turbulence. High-resolution storm data from radar reflectivity or satellites may provide some indication of the likelihood of convective turbulence development, but cannot pinpoint its location or severity. The NCAR/NEXRAD Turbulence Detection Algorithm (NTDA) uses ground-based Doppler weather radar data to measure in-cloud turbulence, with a focus on identifying convective turbulence hazards. NTDA utilizes Level II data from the U.S. network of WSR-88Ds (NEXRADs) to produce real-time, rapid-update, three-dimensional mosaics of in-cloud turbulence. An NTDA product is also produced operationally in the Taiwan Advanced Operational Aviation Weather System using NEXRAD and Gematronik radar data. NTDA turbulence maps are suitable for tactical use by pilots and airline dispatchers and for providing input to comprehensive turbulence nowcasts. They also provide information about storm evolution useful for studying the relationship of turbulence production to thunderstorm dynamics and kinematics. This chapter motivates and describes the NTDA and discusses its performance.

Williams, P. D. and Joshi, M. M.

"CLEAR-AIR TURBULENCE IN A CHANGING CLIMATE"

In Aviation Turbulence, edited by R. Sharman and T. Lane, Chapter 23, 2016, Springer International Publishing Switzerland, pp. 465-480.

How might the processes generating clear-air turbulence change in a warmer world? We know that observations support an association between clear-air turbulence and shear instability. We also know that the upper atmospheric wind shears are changing in response to greenhouse gas forcing. In particular, theoretical reasoning and climate model simulations both suggest that the vertical shear in horizontal wind is increasing in magnitude at typical aircraft cruising altitudes in the middle latitudes,

especially in the winter months in each hemisphere. This increased shearing implies that clear-air turbulence may itself be changing because of climate change. This chapter reviews the various lines of observational and model-based evidence for trends in clear-air turbulence, by analyzing data from turbulence encounters with aircraft, turbulence diagnosed from reanalysis datasets, passenger injuries caused by turbulence, and turbulence diagnosed from climate models. The possibility of anthropogenic trends in clear-air turbulence opens a whole new field of academic study, which exists at the interface between the two scientific disciplines of aviation turbulence and climate change. We call for future work to improve our understanding of this poorly understood but potentially important impact of climate change.

Williamson, C. H. K.

"DYNAMICS AND INSTABILITIES OF VORTEX PAIRS IN OPEN FLOW OR CLOSE TO THE GROUND"

International Workshop on Fundamental Issues Related to Aircraft Trailing Wakes, Marseille, France, May 2008

We present results on the spatial development of delta wing trailing vortices, and we briefly mention the temporal development of vortex pairs, and finally present studies of vortex pair dynamics approaching the ground. We have studied the case of the temporal growth of vortex pairs. Comparisons between experiment and theory, for the growth rates of the long-wave instability, appears to be very good. The vortex pair pinches off to form vortex rings. Interestingly, the long-time development involves oscillations of the elliptically-shaped rings, and can lead to a new phenomenon, whereby the vortex rings can re-reconnect back into the original vortex pair configuration. We also study the spatial development of vortex pairs (generated from a delta wing), where we find three distinct instability length scales. By imposing disturbances on the delta wing incident velocity, we find that the largest-scale (Crow) instability is receptive to a range of wavelengths. Our DPIV measurements of instability growth rate, considering the circumferential velocity profile as well as the axial velocity, are compared with the theory of Widnall et al, without ad-hoc assumptions. There is good agreement, even though the vortices are fat, and there is substantial axial flow. Finally, we shall show new results concerning the dynamics and instabilities of vortex pairs as they approach the ground. In essence, in the presence of the ground the long wavelength instability can be inhibited. As one might expect, there exists a critical initial formation height, above which the vortices reconnect and form vortex rings. Below this height, the incipient Crow instability develops, but due to the ground effect, can apparently even reverse the initial phase of the wavy instability.

Williamson, C. H. K., Leweke, T. and Miller, G. D.

"FUNDAMENTAL INSTABILITIES IN SPATIALLY-DEVELOPING WING WAKES AND TEMPORALLY-DEVELOPING VORTEX PAIRS"

1998 ASME Fluids Engineering Division Summer Meeting, June 1998, Washington, DC

In this presentation we include selected results which have originated from vortex dynamics studies conducted at Cornell, in collaboration with IRPHE, Marseille. These studies concern, in particular, the spatial development of delta wing trailing vortices (Miller & Williamson, 1998), and the temporal development of counter-rotating vortex pairs (Leweke & Williamson, 1998a, 1998b). There are clear similarities in the instabilities of both these flows, as shown in our laboratory-scale studies. At full-scale, the trailing vortices behind wings can reach considerable strengths, and represent a danger to following aircraft, especially smaller ones, due to the rolling moment they induce.

Williamson, C. H. K., Leweke, T. and Miller, G. D.

"WING WAKE VORTICES AND TEMPORAL VORTEX PAIR INSTABILITIES"

Lecture Notes in Physics, Vol. 566, 2001, pp. 379-400

In the case of the temporal growth of vortex pairs, formed by the closing of a pair of long flaps underwater, we find two principal instabilities; namely, a long wavelength Crow instability, and a short-wavelength 'elliptic' instability. Comparisons between experiment and theory for the growth rates of the long-wave instability, over a range of perturbed wavelengths, appears to be very good. The vortex pair 'pinches off', or reconnects, to form vortex rings in the manner assumed to occur in contrails behind jet aircraft. We discover a symmetry-breaking phase relationship for the short-wave disturbances growing in the two vortices, which we show to be consistent with a kinematic matching condition between the two disturbances. Further results demonstrate that this instability is a manifestation of an elliptic instability, which is here identified for the first time in a real open flow. We therefore refer to this flow as a 'cooperative elliptic' instability. The long-term evolution of the flow involves the inception of secondary miniscule vortex pairs, which are perpendicular to the primary vortex pair.

Williamson, G. G., Snedeker, R. S. and Donaldson, C. duP.

"ON THE OPERATION OF AIRCRAFT IN THE WAKES OF OTHER AIRCRAFT"

Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 136-149

The study explores the possible benefits of the operation of one aircraft in the wake of another through utilization of the energy contained in the wake vortices.

Willis, D. J., Peraire, J. and White, J. K.

"A COMBINED pFFT-MULTIPOLE TREE CODE, UNSTEADY PANEL METHOD WITH VORTEX PARTICLE WAKES"

AIAA Paper No. 2005-0854, Reno, NV, January 200.

The two main difficulties in using potential flow solvers in aircraft design are the limitations on the number of discretization elements and the user expertise and effort required to specify the wake location. In the paper, we present an automatic wake generation strategy for a potential flow solver, and accelerate the method using a pFFT-Fast Multipole Tree algorithm. The combined method can be used to simulate both steady and unsteady flows. The steady state solution is achieved by running an unsteady flow simulation until it reaches a steady state.

Willis, D. J., Peraire, J. and White, J. K.

"A COMBINED pFFT-MULTIPOLE TREE CODE, UNSTEADY PANEL METHOD WITH VORTEX PARTICLE WAKES"

International Journal for Numerical Methods in Fluids, Vol. 53, 2007, pp. 1399-1422.

Potential flow solvers for 3-D aerodynamic flows are commonly used in industrial applications. Two main difficulties preventing the even more widespread use of these codes are the limitations on the number of discretization elements and the user expertise and effort required to specify the wake location. In the paper we present an automatic wake generation strategy for a potential flow solver, and accelerate the method using a pFFT-Fast Multipole Tree algorithm. The combined method can be used to simulate both steady and unsteady flows. The steady state solution is achieved by running an unsteady flow simulation until it reaches a steady state. Computation results are given to demonstrate that the method is fast enough to automatically simulate entire heaving and flapping wing crafts in under an hour on a desktop computer.

Willmarth, W. W., Tryggvason, G., Hirs, A. and Yu, D.

"VORTEX PAIR GENERATION AND INTERACTION WITH A FREE SURFACE"

Physics of Fluids, Vol. A1, No. 2, February 1989, pp. 170-173.

Two vertical, rotating flaps are used to generate a vortex pair beneath a free surface. Vortex pair formation, propagation, and interaction with a free surface are described. Numerical simulations for inviscid flow about a constant upwash sheet of vorticity beneath a free surface agree with experiment up to the time that turbulent mixing occurs during interaction with the free surface. The spacing between the vortex pairs then becomes larger than the calculated spacing. The experiments and lines of marked particles included in the simulations show fluid ingestion and transport toward the free surface.

Wilmott, P.

"ON THE DISTRIBUTION OF IMPULSES IN INVISCID, INCOMPRESSIBLE FLOW -- THE INDUCED DOWNWASH ON A ROTATING WING"

Acta Mechanica, Vol. 61, 1986, pp. 129-137.

We consider the prescribing of singularities in inviscid fluid flows by including Dirac delta functions in the Euler momentum equation. Examples are given of the modeling of the flows due to the lifting bodies, in particular that due to a wing simultaneously translating and rotating and find that the induced downwash due to the trailing vortex wake.

Wilson, D. J., Brashears, M. R., Carter, E. A. and Shrider, K. R.

"WAKE VORTEX AVOIDANCE SYSTEM"

FAA-RD-72-108, December 1972, Lockheed Missiles & Space Company, Huntsville, AL

This report provides a conceptual design for a predictive-detective system to: (a) predict the movement and decay of aircraft-generated vortices in air corridors near the air terminal using forecast meteorological conditions; (b) periodically update the prediction by monitoring vortex movements; (c) provide a forecast of separation requirements for optimum aircraft spacing according to prevailing vortex conditions, and (d) provide a wave off (or hold) capability for rare cases when vortices stray unpredictably into a 'hazard' zone. In addition, the report discusses the predictive system computer model including the meteorological input data and the fluid mechanics used to develop the vortex prediction. Fluid mechanic discussions include wind, wind shear and buoyancy effects upon vortex transport and decay. Computer runs are presented to demonstrate vortex transport under numerous meteorological conditions at example airports. Finally, a test for proof of the predictive system concept is discussed.

Wilson, D. J., Brashears, M. R., Carter, E. A., Shrider, K. R., Hallock, J. N. and Szymkowicz, J. S.

"WAKE VORTEX AVOIDANCE SYSTEM"

Proceedings of the Accident Prevention Forum on Aircraft Approaches and Landings, NTSB, October 1972, pp. 1-15.

Four options exist for wake vortex avoidance systems: a predictive concept in which the aircraft spacings are set based upon predicted meteorological conditions; a surface sensor concept in which surface winds are used to determine whether crosswinds are above a predetermined threshold which in turn indicates that minimum spacings may be used; a scanning sensor concept in which active sensors are employed to track the vortices and a wave off is called for if the vortices are still within an approach corridor when a following aircraft arrives; and a predictive-detective concept in which vortex movement is monitored and used to update predictions of what separations may be safely employed.

Wilson, D. J., Krause, M. C., Coffey, E. W., Huang, C. C., Edwards, B. B., Shrider, K. R., Jetton, J. L. and Morrison, L. K.

"DEVELOPMENT AND TESTING OF LASER DOPPLER SYSTEM COMPONENTS FOR WAKE VORTEX MONITORING. VOL. 1: SCANNER DEVELOPMENT, LABORATORY AND FIELD TESTING AND SYSTEM MODELING"

NASA CR-120466, August 1974, Lockheed Missiles & Space Company, Huntsville, A.

Three elevation and range scanners were developed for the NASA LDV systems. The elevation scanners provide a capability to manually point the LDV telescope at operator selected angles from 3.2 to 89.6 degrees within 0.2 degrees or to automatically scan the units between operator chosen limits at operator chosen rates of 0.1 to 0.5 Hz. Likewise, the range scanners provide a capability to manually adjust the focal point of the system from a range of 32 meters to 896 m; range and elevation scanner controls are designed to allow simultaneous range and elevation scanning so as to provide finger scan patterns, arc scan patterns and vertical line scan patterns.

Wilson, D. J., Krause, M. C., Craven, C. E., Edwards, B. B., Coffey, E. W., Huang, C. C., Jetton, J. L. and Morrison, L. K.

"CONDUCT OVERALL TEST OPERATIONS AND EVALUATE TWO DOPPLER SYSTEMS TO DETECT, TRACK AND MEASURE VELOCITIES IN AIRCRAFT WAKE VORTICES"

NASA CR-120600, December 1974, Lockheed Missiles & Space Company, Huntsville, A.

The report discusses a program plan, a critical path review of events necessary to check out the laser Doppler systems, and the results of the tests. The tests included noise and wind tests, large blower flowfield tests, single unit (1-D) flyby tests. The scanning laser Doppler systems were found to be capable of accurately tracking aircraft wake vortices from small aircraft or large aircraft and in almost any type of weather.

Wilson, D. J., Shrider, K. R. and Lawrence, T. R.

"FEASIBILITY OF WAKE VORTEX MONITORING SYSTEMS FOR AIR TERMINALS"

HREC 6668-1, August 1972, Lockheed Missiles & Space Company, Huntsville, AL

Wake vortex monitoring systems, especially those using laser Doppler sensors, were investigated under this contract. The initial phases of the effort involved talking with potential users (air traffic controllers, pilots, etc.) of a wake vortex monitoring system to determine system requirements from the user's viewpoint. These discussions involved the volumes of airspace to be monitored for vortices, and potential methods of using the monitored vortex data once the data are available. A subsequent task led to determining a suitable mathematical model of the vortex phenomena and developing a mathematical model of the laser Doppler sensor for monitoring the vortex flow field. The mathematical models were used in combination to help evaluate the capability of laser Doppler instrumentation in monitoring vortex flow fields both in the near vicinity of the sensor (within 1 km) and at long ranges (10 km).

Wilson, D. J., Zalay, A. D., Brashears, M. R., Craven, C. E., Shrider, K. R. and Jordan, A. J.

"WAKE FLOW MEASUREMENTS WITH A MOBILE LASER DOPPLER VELOCIMETER SYSTEM"

AIAA Paper 78-0823, April 1978, San Diego, CA.

Wake flow measurements were conducted with a mobile laser Doppler velocimeter (LDV). The measurements included surveys of aircraft wake vortices behind a B-747 aircraft, aircraft carrier wake measurements from aboard the U.S.S. Nimitz, and tower wake measurements for a 100-kW wind turbine. Results of these tests demonstrated that a mobile ground-based LDV is a versatile and useful tool for the measurement of full-scale three-dimensional wake flows. The potential is demonstrated for utilization of this system to study complex wakes for a variety of applications.

Wilson, D. J., Zalay, A. D., Brashears, M. R., Craven, C. E., Shrider, K. R. and Jordan, A. J.

"FULL-SCALE WAKE FLOW MEASUREMENTS WITH A MOBILE LASER DOPPLER VELOCIMETER"

J. Aircraft, Vol. 16, No. 3, March 1979, pp. 155-161

Wake flow measurements were conducted with a mobile Laser Doppler Velocimeter (LDV). The measurements included surveys of aircraft wake vortices behind a B-747 aircraft, aircraft carrier wake measurements from aboard the U.S.S. Nimitz, and tower wake measurements for a 100-kW wind turbine. Results of these tests demonstrated that a mobile ground-based LDV is a versatile and useful tool for the measurement of full-scale three-dimensional wake flows. The potential is demonstrated for utilization of this system to study complex wakes for a variety of applications.

Wilson, J. D. and Loth, J. L.

"REAL TIME DEVELOPMENT OF THE WAKE OF A FINITE WING"

M.S. Thesis, February 1974, West Virginia Univ., Morgantown, WV

A real time, three-dimensional method is presented to monitor the development of the wake generated by a finite wing, which suddenly begins to produce lift in an irrotational, incompressible fluid. The wake is represented by equal strength vortex filaments which are bounded by a lifting line at the wing position and a starting vortex which washes downstream with the free stream velocity. The geometric angle of attack of the wing was changed with time so that only one starting vortex was shed and the circulation of the bound vortex remains constant. The computational time was significantly reduced by neglecting the component of induced velocity in the free-stream direction. The Biot-Savart law was needed to calculate the wake deformation of an Army O-1 aircraft, for which experimental results have been reported by B. W. McCormick. Experimental and theoretical values for circulation at contours in the wake showed agreement although the experimental results, which consisted of contours of constant vorticity, were limited to a region near the wing tips and within a chord length of the wing trailing edge.

Wilson, J. M.

"WAKE VORTEX ENCOUNTER RESEARCH"

Langley Aerospace Research Summer Scholars, Part 2, January 1995, pp. 817-823

The National Aeronautics and Space Administration (NASA) is conducting research to improve airport capacity by reducing the separation distance between aircraft. The limiting factor in reducing separation distances and improving airport capacity is the wake vortex hazard. The ability to accurately model wake vortices and predict the outcome of a vortex encounter is critical in developing a system to safely improve airport capacity. This is the focus of the wake vortex research being done at NASA Langley Research Center. This paper will concentrate on two topics. The first topic is the control system developed for the Boeing 737 free flight model in support of vortex encounter tests to be conducted in the 30- by 60-foot tunnel at NASA Langley Research Center later this year. The second topic discussed is the limited degree of freedom trajectory generation study that is being conducted to determine the relative severity of a multitude of paths through a wake vortex.

Winant, C. D. and Browand, F. K.

"VORTEX PAIRING: THE MECHANISM OF TURBULENT MIXING-LAYER GROWTH AT MODERATE REYNOLDS NUMBERS"

J. Fluid Mech., Vol. 63, Part 2, April 1974, pp. 237-255

A mixing layer is formed by bringing two streams of water, moving at different velocities, together in a Lucite-walled channel. The Reynolds number, based on the velocity difference and the thickness of the shear layer, varies from about 45, where the shear layer originates, to about 850 at a distance of 50cm. Dye is injected between the two streams just before they are brought together, marking the vorticity-carrying fluid. Unstable waves grow, and fluid is observed to roll up into discrete two-dimensional vortical structures. These turbulent vortices interact by rolling around each other, and a single vortical structure, with approximately twice the spacing of the former vortices, is formed. This pairing process is observed to occur repeatedly, controlling the growth of the mixing layer. A simple model of the mixing layer contains, as the important elements controlling growth, the degree of non-uniformity in the vortex train and the 'lumpiness' of the vorticity field.

Winckelmans, G. S.

"TOPICS IN VORTEX METHODS FOR THE COMPUTATION OF THREE- AND TWO-DIMENSIONAL INCOMPRESSIBLE FLOWS"

PhD Thesis, Feb. 1989, California Institute of Technology, Pasadena, CA.

Contributions to vortex methods for the computation of incompressible unsteady flows are presented. Three methods are investigated, both theoretically and numerically. The first method is the inviscid method of vortex filaments in three dimensions, and the following topics are presented: (a) review of the method of regularized vortex filaments and of convergence results for multiple-filament computations, (b) modeling of a vortex tube by a single filament convected with the regularized Biot-Savart velocity applied on the centerline: velocity of the thin filament vortex ring and dispersion relation of the rectilinear filament, and (c) development of a new regularization of the Biot-Savart law

that reproduces the lowest mode dispersion relation of the rectilinear vortex tube in the range of large to medium wavelengths. Next the method of vortex particles in three dimensions is investigated, and the following contributions are discussed: (a) review of the method of singular vortex particles: investigation of different evolution equations for the particle strength vector and weak solutions of the vorticity equation, (b) review of the method of regularized vortex particles and of convergence results, and introduction of a new algebraic smoothing with convergence properties as good as those of Gaussian smoothing, (c) development of a new viscous method in which viscous diffusion is taken into account by a scheme that redistributes the particle strength vectors, and application of the method to the computation of the fusion of two vortex rings at $Re=400$, and (d) investigation of the particle method with respect to the conservation laws and derivation of new expressions for the evaluation of the quadratic diagnostics: energy, helicity and enstrophy. The third method considered is the method of contour dynamics in two dimensions. The particular efforts presented are (a) review of the classical inviscid method and development of a new regularized version of the method, (b) development of a new vector particle version of the method, both singular and regularized: the method of particles of vorticity gradient, (c) development of a viscous version of the method of regularized particles and application of the method to computation of the reconnection of two vortex patches of same sign vorticity, and (d) investigation of the particle method with respect to the conservation laws and derivation of new expressions for the evaluation of linear and quadratic diagnostics.

Winckelmans, G. S.

"THE VORTEX FORECAST SYSTEM (VFS): PREDICTION OF TRAJECTORIES AND DECAY FOR AIRCRAFT WAKE VORTICES IN AN OPERATIONAL ENVIRONMENT"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001

The VFS is an operational wake vortex predictor system based on the Method of Discrete Vortices (MDV). It was developed under contract with Transport Canada and its Transportation Development Center, during 6 Phases (from 1993 to 2000) and by an international team. The VFS is now a sophisticated, validated, and mature technology: one that can be used in real-time operational systems. It could nevertheless be further validated and improved. It handles: Creation of the initial near wake using either SABIGO's detailed Near Wake DataBase (NWDB) or the simplified Universal Near Wake (UNW) which then assumes the 'universal' circulation profile for aircraft wakes shortly after rollup; Modelling of wake transport, using the vortex-induced velocities and the cross-wind velocity profile; Modelling of the slow wake decay, using the atmospheric turbulence profile (either EDR decay model or TKE decay model) and of the fast decay time (time to demise as function of EDR); Modelling of inviscid near ground effects (by image discrete vortices) and of viscous in ground effects (by injection of secondary discrete vortices from the ground); Modelling of non-uniform wind shear effects (by additional vertical velocities acting on the discrete vortices); Modelling of stratification effects, using the atmospheric stratification profile (model implementation is ongoing). For simulations of landing, the VFS is run in multiple cross-plane 'gates' (typically 5 gates, ranging from the intercept plane to the touchdown plane), so that a more realistic space-time vortex evolution is obtained. It can also be used for closely-spaced parallel runway applications.

Winckelmans, G. S. and Leonard, A.

"CONTRIBUTIONS TO VORTEX PARTICLE METHODS FOR THE COMPUTATION OF THREE-DIMENSIONAL INCOMPRESSIBLE UNSTEADY FLOWS"

Journal of Computational Physics, Vol. 109, 1993, pp. 247-273

Recent contributions to vortex particle methods for the computation of three-dimensional incompressible unsteady flows are presented. Both singular and regularized vortex particle methods are reviewed, along with an investigation of different evolution equations for the particle strength vector. For the regularized method, a new algebraic smoothing is presented with convergence properties equal to those of Gaussian smoothing. A version of the regularized method which can account for viscous diffusion is developed using a scheme that redistributes the particle strength vectors. Finally, particle methods are investigated with respect to conservation laws, and new expressions for the quadratic diagnostics, energy, helicity, and enstrophy are derived.

Winckelmans, G. S. and Ploumhans, P.

"ON THE EFFICIENT SIMULATION OF VORTEX WAKES IN GROUND EFFECT, INCLUDING THE VISCOUS INTERACTION WITH THE GROUND: SAMPLE COMPUTATIONS USING THE VORTEX PARTICLE METHOD COMBINED WITH THE BOUNDARY ELEMENT METHOD"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 77-8.

During vortex wake generation and evolution near the ground, the presence of the ground is strongly affecting the evolution of the wake - vorticity is continuously being produced at the ground because the ground acts as a solid boundary to the wake flow. This ground-generated vorticity is also continuously being diffused from the ground into the wake flow. The simplest picture which consists in assuming that the ground only cancels the normal velocity is not physical because it allows for a tangential velocity at the ground. A fully Lagrangian fast code based on the combination of the vortex particle method with the boundary element has been developed. The boundary elements are M discrete vortex sheet 'panels' whose strength is computed at every time step to ensure the condition of zero tangential velocity at the ground plane. The M vortex sheets are also diffused into the flow, at every time step, in a manner which is consistent with the diffusion equation for vorticity (assuming an effective 'turbulence' viscosity) and accurate. Sample computations have been carried out and will be presented. One main conclusion is that the viscous ground indeed has a strong effect on the global lateral and vertical displacement of the wake vortices. The value of the effective turbulence viscosity has a strong incidence on the diffusion of ground-generated vorticity and hence on the global decay of the wake vortices. In the presence of crosswind, a strong asymmetry appears between port and starboard vortices: asymmetry in vertical position and in decay rate.

Winckelmans, G. S. and Ploumhans, P.

"PREDICTION OF AIRCRAFT WAKE VORTICES DURING TAKEOFF AND LANDING, PHASE 4"

USGRDR0024, 1999, Transportation Development Center, Civil Aviation Directorate, Montreal (Quebec), Canada.

This report outlines the background of two versions of the method of discrete vortices and their advantages and limitations in the modelling and simulation of aircraft wake vortices. The treatment of the viscous interaction with the ground is also described for each method. Results using version B in ground effect studies, with and without cross-wind, are presented, including the simulation of a real case and comparison with version A. Activities for the next phase of a wake vortex prediction project are also proposed.

Winckelmans, G. S. and Ploumhans, P.

"PREDICTION OF AIRCRAFT WAKE VORTICES DURING TAKEOFF AND LANDING - PHASE 4"

TP-13374E, March 1999, Universite Catholique de Louvain, Louvain-la-Neuve, Belgium

This report outlines the background of two versions of the Method of Discrete Vortices (MDV-A and MDV-B) and their advantages and limitations in the modeling and simulation of aircraft wake vortices. The treatment of the viscous interaction with the ground is also described for each method. For a large number, N , of discrete vortices, a fast order $O(N \log N)$ tree-code is used to increase the computational efficiency. MDV-A is used for small N simulations as needed for a real-time Vortex Forecast System (VFS). MDV-B is fine-grain (large N) and efficient (because of the fast tree code) but is not real-time; it is used for detailed wake studies and for MDV-A validation. Results from MDV-B in-ground effect studies, with and without cross-wind, are presented, including the simulation of a real case and the comparison with MDV-A. Activities for the next phase of the Wake Vortex Prediction Project are proposed.

Winckelmans, G., Cocle, R., Dufresne, L. and Capart, R.

"VORTEX METHODS AND THEIR APPLICATION TO TRAILING WAKE VORTEX SIMULATIONS"

C. R. Physique, Vol. 6, 2005, pp. 467-486

Vortex methods are competitive for simulating incompressible unsteady flows, because they have negligible dispersion error and good energy conservation. The various methods are presented, including the recent developments: particle redistribution, diffusion, relaxation (by projection), efficient solvers (fast multipole method, vortex-in-cell method, hybrid method) and parallel computer implementations. Examples relating to wing/aircraft trailing wake vortices are presented: 2-D and 3-D, inviscid and viscous, direct numerical simulation and large eddy simulation. We consider wake roll-ups, vortex tube dynamics, 3-D instabilities and the complexity/turbulence they produce. A vortex system in ground effects is also presented.

Winckelmans, G., Cocle, R., Dufresne, L., Capart, R., Bricteux, L., Daeninck, G., Lonfils, T., Duponcheel, M., Desenfans, O. and Georges, L.

"DIRECT NUMERICAL SIMULATION AND LARGE-EDDY SIMULATION OF WAKE VORTICES: GOING FROM LABORATORY CONDITIONS TO FLIGHT CONDITIONS"

European Conf. on Computational Fluid Dynamics, ECCOMAS CFD 2006, Delft, The Netherlands

This paper aims at presenting DNS and LES as applied to the simulation of vortex wakes: in laboratory conditions (moderate to medium Reynolds numbers) and up to real aircraft conditions (high to very high Reynolds numbers). Only incompressible flows are considered. DNS and LES are able to capture complex 3-D physics provided one uses high quality numerical methods: methods with negligible numerical dissipation (i.e., methods that conserve energy in absence of viscosity and/or subgrid modelling) and with low dispersion errors (to properly transport complex vortical structures). Methods that can do that are: spectral methods, high order finite difference methods, and vortex-in-cell methods. As the problems of interest are of large spatial extent and contain vortices with small cores, it is also essential that the methods be efficiently parallelized. The recent multiscale models, that act solely on the high wavenumber modes of the LES, are seen to be most appropriate.

Winckelmans, G., Desenfans, O., Barbaresco, F., Deltour, J.-C., Pham, K., Frech, M., Gerz, T., Holzaepfel, F., van Baren, G., Speijker, L., Verhoogt, T. and Vidal, A.

"THE ATC-WAKE PREDICTOR SYSTEM AND ITS POTENTIAL USE TO INCREASE THE CAPACITY AT AIRPORTS"

Proc. Joint International Symposium on Sensors and Systems for Airport Surveillance, JISSA 2005, Paris, June 20-21, 2005.

The ATC-Wake project is funded by the EC under the 'Information Society Technology' Programme. Main objective is the development of an Air Traffic Control Wake Vortex Safety and Capacity Integrated Platform (IP). This IP is used to evaluate interoperability with existing ATC systems, to assess possible safety and capacity improvements, and to evaluate operational usability and acceptability for air traffic controllers. It constitutes an essential step for installation of an 'integrated ATC decision support system' at airports, enabling air traffic controllers to safely apply new optimized weather-based aircraft spacing. The system integrates four new wake-vortex related subsystems: a Separation Mode Planner component (based on a weather forecasting and nowcasting system), a Predictor component (based on weather and wake sensors), a Monitoring and Alerting component (which notifies the air traffic controllers in case of a discrepancy between prediction and detection information), as well as Human Machine Interfaces to the controllers. Used in combination with new wake vortex safety regulation, the ATC-Wake System will provide both tactical and strategic benefits, while maintaining the required level of safety. This paper focuses on the ATC-Wake Predictor, which predicts for individual aircraft the wake vortex behavior in the pre-defined arrival or departure area(s). Prediction is performed using probabilistic wake vortex prediction models fed by real-time meteorological data (most recent nowcast data as well as ground or down-linked airborne measurements) from the time the aircraft reaches a critical arrival area entry until it lands and from the take-off until it leaves the critical departure area.

The prediction quality being directly related to input data quality (meteorological and radar data), a safety buffer is applied to satisfy accuracy requirements of Air Traffic Controllers and/or regulatory authorities. The prediction is updated in short intervals (6 seconds) and the information is provided to ATC through a HMI in the form of a Wake Vortex Vector. It is also vaulted/assessed by wake vortex measurements (performed by the Detector).

Winckelmans, G., Duquesne, T., Treve, V., Desenfans, O. and Bricteux, L.

"SUMMARY DESCRIPTION OF THE MODELS USED IN THE VORTEX FORECAST SYSTEM (VFS)"

Universite Catholique de Louvain (UCL), Internal Report, April 2005

This document provides a brief description of the Vortex Forecast System (VFS) principles and the different models used. The VFS is a deterministic and operational wake vortex predictor (transport and decay) previously developed by an international team (partners from Russia (SABIGO), Canada and Belgium) under contract with Transport Canada (TC) and its Transportation Development Center (TDC). The VFS as it was at the end of the TC/TDC funded project is described in [1]. It is continuously enhanced, also by research conducted at Universite Catholique de Louvain (UCL), Belgium, in the Division TERM (group of Prof. G. Winckelmans). This document presents the VFS version as of April 1, 2005, thus including the improvements added by UCL after completion of the TC/TDC funded project. It was written for 'open communication' purposes: so as to clearly explain the global approach and the models implemented so far.

Winckelmans, G., Treve, V. and Desenfans, O.

"REAL-TIME SAFETY ADVISING SYSTEM IN REDUCED WV SEPARATIONS OPERATION, AS DEVELOPED IN ATC-WAKE"

Second Workshop WakeNet2-Europe, 'Capacity Gains as Function of Weather and Weather Prediction Capabilities', Langen, November 2004.

The ATC-Wake project started two years ago. The main objective of this project is to develop and build a wake vortex safety and capacity Integrated Platform (IP). This platform will be used to evaluate interoperability with existing ATC systems, to assess possible safety and capacity improvements, to evaluate operational usability and acceptability, and to make a technological implementation plan. This platform is an essential step that will lead to installation of an integrated ATC decision support system at airports, enabling air traffic controllers to apply new optimized weather-based aircraft spacing. According to the user and system requirements defined during the first phase of the project, two main subsystems are developed. The first subsystem, called the 'Separation Mode Planner' (SMP), is dedicated to the forecasting of a safe landing rate about 40 minutes in advance (planning phase). This time constraint is imposed by the fact that, at most major airports, an Arrival MANager system (AMAN) is used to organize the traffic en-route before the entrance in the TMA. The SMP is mainly based on weather forecasting coupled to safety assessment of the various conceivable separation distances. The second subsystem, called the 'Predictor' constitutes the real-time part of the ATC-Wake system (tactical

phase). Here 'Predictor' is not just 'wake vortex prediction' (using VFS and P2P); it means the real-time subsystem used to assess, during the tactical phase, the suitability of the separations previously proposed by the SMP. This system merges, on one hand, input data from the weather monitoring/nowcasting systems and from the airport surveillance systems, and, on the other hand, databases describing airport layout and aircraft characteristics. In the 'virtual IP' developed so far in ATC-Wake, the various data provider systems are 'emulated': using the results of an airport simulation (TAAM simulation by Eurocontrol) connected to a radar emulator (from Thales) and a weather database (DLR databases of Wake-OP and Wake-TOUL campaigns). The 'Predictor' determines, in real-time, the part of the glide slope potentially affected by wake vortices. The information is provided on the air traffic controller screen (using a 'wake vortex vector') through a human machine interface (specially developed by NLR and evaluated through tower simulator sessions). We here propose to give a global presentation of the 'Predictor' subsystem: principles and functionalities (as described above), and demonstration by using the virtual environment (emulators) of the future ATC-Wake IP.

Winkler, S. and Perras, G.

"AN ANALYSIS OF WAKE VORTEX LIDAR MEASUREMENTS AT LAGUARDIA AIRPORT"

ATC-318, November 2004, MIT Lincoln Lab., Lexington, MA

Most of the research into the wake vortex hazard has concentrated on the in-trail encounter scenario for arrivals. At LaGuardia Airport, wake vortex spacings are applied to arrivals on runway 22 following a heavy departure on the intersecting runway 31, resulting in delay and increased workload for controllers. Previous analysis of this problem led to a recommendation for a measurement campaign to collect data on the behavior of wake vortices generated by departing heavy aircraft. In April of 2004, MIT Lincoln Laboratory deployed its wake vortex lidar system to measure such wakes at LaGuardia. Additionally, wind speed and turbulence data were collected with the hope of correlating wake behavior with the local atmospheric conditions. Analysis of the lidar data indicates that the system was able to acquire and track vortices from departures, a task not proven prior to this deployment. Further, vortices were seen to transport toward the threshold of runway 22, verifying an assumption based on analysis of the winds that wake transport is not a solution in this case. The quantity and type of data collected were insufficient to formulate a clear relationship between atmospheric turbulence and vortex decay. However, it may be possible to develop such a model by exploiting the data gathered during previous lidar deployments.

Winkler, S., Perras, G. and Cole, R.

"WAKE VORTEX FIELD MEASUREMENT PROGRAM AT DENVER, CO DATA GUIDE"

Report F19628-00-C-0002, March 2004, MIT Lincoln Lab, Lexington, MA.

The FAA and NASA direct a joint wake vortex program that draws on the expertise of several organizations. In support of this program, MIT Lincoln Laboratory operates a mobile continuous-wave lidar.

Winter, H.

"RESEARCH AND DEVELOPMENT PROGRAM FOR A WAKE VORTEX WARNING SYSTEM IN GERMANY"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 3-1 - 3-7

The necessity to use Wake Vortex (WV) separations for aircraft on their final approach to an airport significantly reduces the available runway landing capacity. In 1984 the German Bundesministerium für Verkehr (BMV) initiated a research program to investigate the possibilities for a reduction of the required WV separations at the airport of Frankfurt. Theoretical studies and measurements taken at the Frankfurt airport have led to the definition of a WV Warning System (WVWS) for this airport. Since 1989 DLR is working on a project to study the potential for capacity improvement at the Frankfurt airport. Amongst several improvements for capacity enhancement, the WVWS was considered and analyzed for capacity benefits. These considerations have led to the definition of a project for the implementation of a WVWS at the Frankfurt airport. In the capacity enhancement study it was found that automation of approach, taxi and departure control is an important precondition for the improvement of the overall capacity situation of an airport like Frankfurt.

Wissink, A. M., Kamkar, S., Pulliam, T. H., Sitaraman, J. and Sankaran, V.

"CARTESIAN ADAPTIVE MESH REFINEMENT FOR ROTORCRAFT WAKE RESOLUTION"

AIAA Paper No. 2010-4554, June 2010, Chicago, Illinois.

We explore the use of high-order algorithms within a block-structured Cartesian adaptive mesh refinement solver to capture shed wakes from rotary-wing vehicles. The adaptive Cartesian solver is used as an off-body solver, in conjunction with a viscous near-body unstructured solver to capture wall boundary layer effects. The off-body solver automatically adapts to resolve time-dependent flow features, refining and coarsening throughout the unsteady simulation, with mesh refinement targeting regions of high vorticity. Accuracy and performance of the adaptive solver are tested for resolving the tip vortices from a wing at angle of attack and the wake of a quarter-scale V-22 helicopter rotor in hover conditions..

Witha, B., Steinfeld, G., Dorenkamper, M. and Heinemann, D.

"LARGE-EDDY SIMULATION OF MULTIPLE WAKES IN OFFSHORE WIND FARMS"

The Science of Making Torque from Wind 2012, published in IOP Journal of Physics: Conference Series Vol. 555, 2014, pp. 012108-1 - 012108-10.

In this study, high-resolution large-eddy simulations of two German offshore wind farms are performed with the LES model PALM in which the turbines are parameterized with an actuator disk approach. The simulation of a single wind farm is realized by a stationary model domain with a

turbulent inflow. Different atmospheric stratifications from slightly stable to unstable have been simulated and their effect on the wake characteristics is investigated. The results show a clear development of the flow within wind farms with large differences between single, double, and triple wakes. The wake deficit is increasing up to the second wake for the neutral and stable boundary layer and up to the third wake in the convective case before reaching a nearly constant value. This is explained with the turbulence intensity being much higher behind the second and subsequent turbines compared to the wake of the first turbine. With increasing atmospheric stability, the wake deficits are shown to be stronger due to reduced turbulence.

Witte, B. M., Schlagenhauf, C., Mullen, J., Helvey, J. P., Thamann, M. A, and Bailey, S. C. C.

"FUNDAMENTAL TURBULENCE MEASUREMENT WITH UNMANNED AERIAL VEHICLES"

AIAA Paper 2016-3584, June 2016, Washington, DC.

This paper addresses the potential of using unmanned aerial vehicles for conducting research in the atmospheric boundary layer. A method of computing wind speed from a moving velocity sensor data is provided. The approach is demonstrated for both five-hole probes and hot-wire probes. Included in the procedure is a technique which was shown to provide an invertible, a posteriori calibration for hot-wire voltage data, demonstrated using data from a mid-afternoon flight of an unmanned aerial vehicle equipped with a single-sensor hot-wire probe. Several bulk and small-scale characteristics from small, fixed-wing unmanned vehicle flights in the convective boundary layer are calculated, and show the potential for extracting a range of both large-scale and small-scale turbulence statistics.

Wittmer, K. S.

"TURBULENT FLOWFIELD DOWNSTREAM OF A PERPENDICULAR AIRFOIL-VORTEX INTERACTION"

PhD Thesis, October 1996, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Experiments were performed to document the turbulent flowfield produced downstream of an airfoil encountering an intense streamwise vortex. This type of perpendicular airfoil-vortex interaction commonly occurs in helicopter rotor flows. The experiments presented here thus provide useful information for the prediction of helicopter noise, particularly BWI noise. Three-component velocity and turbulence measurements were made in unprecedented detail using a computerized miniature four-sensor hot-wire probe system; revealing much about the structure and behavior of this flow over a range of conditions. The interaction between the vortex and the airfoil wake leaves the vortex surrounded by a large region of intense turbulence unlike the turbulence surrounding an isolated vortex. Even for close separations, the vortex core passes the airfoil virtually unchanged. However, vorticity of opposite sign is shed by the airfoil in response to the angle of attack distribution induced by the vortex resulting in an unstable circulation distribution according to Rayleigh's criterion. Simple theoretical models adequately describe the shed vorticity distribution of the airfoil and the unstable circulation distribution it imparts on the vortex. As the flow develops, the vortex continuously distorts the airfoil wake. The strain rates imparted by the vortex on the spanwise vorticity contained in the

airfoil wake result in an anisotropic, turbulence producing stress field. For several chord lengths downstream, the vortex core remains laminar and little change is seen in the unstable circulation distribution. While the vortex core is laminar, turbulent fluctuations measured in the core are the result of inactive wandering motions and the characteristic length and velocity scales of the flat portion of the vortex wake appear to be appropriate scales for the fluctuations. Eventually, the vortex core becomes turbulent as indicated by an increase in high frequency velocity fluctuation levels of more than an order of magnitude. Subsequently, the circulation distribution reorganizes to a stable distribution. A loss in core circulation occurs due to a decrease in the peak tangential velocity which is proportionately larger than the increase in the vortex core radius. The peak tangential velocity decreases to the point where it is exceeded by the axial velocity deficit -- another unstable situation. These effects increase with decreased separation between the vortex and the airfoil, but appear to be largely independent of airfoil angle of attack and only weakly dependent upon vortex strength.

Wittmer, K. S. and Deavenport, W. J.

"INTERACTION OF A STREAMWISE VORTEX WITH A FULL-SPAN BLADE"

AIAA Paper No. 95-2214, San Diego, CA, June 1995

The perpendicular interaction of a streamwise vortex with an infinite span blade was studied in incompressible flow. Three-component velocity and turbulence measurements were made using a sub-miniature four sensor hot-wire probe. Vortex core parameters (radius, peak tangential velocity, circulation, and centerline axial velocity deficit) were determined as functions of blade-vortex separation, streamwise position, blade angle of attack, vortex strength, and vortex size. Only a portion of this data set is presented here. The interaction of the vortex with the blade causes substantial changes in the vortex parameters for separations less than 0.375 chords. Core radius increases while peak tangential velocity decreases with the effect being greater for smaller separations. Simultaneously increasing the vortex generator and interaction blade angles of attack (for a fixed separation distance) also causes a dramatic weakening of the vortex core when compared to the undisturbed values. The scale and intensity of the turbulent region is seen to increase dramatically. The downstream development of the flow shows that the interaction of the blade wake with the vortex is the cause of the changes in the core parameters. Instability in the vortex core appears to be the catalyst for the magnification of the size and intensity of the turbulent flowfield downstream of the interaction.

Wittwer, A. R., Dorado, R., Alvarez y Alvarez, G., Degrazia, G. A., Loredou-Souza, A. M. and Bodmann, B.

"FLOW IN THE WAKE OF WIND TURBINES: TURBULENCE SPECTRAL ANALYSIS BY WIND TUNNEL TESTS"

American Journal of Environmental Engineering, Vol. 6, No. 4A, 2016, pp. 109-115.

The interaction between the incident wind and wind turbines in a wind farm causes mean velocity deficit and increased levels of turbulence in the wake. The turbulent flow is characterized by the superposition of wind turbine wakes. In this work, the technique of turbulence spectral evaluation for

reduced scale models in a boundary layer wind tunnel is presented, and different measurements of velocity fluctuations are analyzed. The results allow evaluating the spectrum for different frequency ranges and the differences of the spectral behavior between the incident wind and the turbine wake flow.

Witzberger, K. E. and Robinson III, J. E.

"ANALYSIS OF EXCESS WAKE VORTEX SEPARATION ON ARRIVAL DELAY"

AIAA Paper 2013-4424, August 2013, Los Angeles, CA.

An analysis is performed to estimate the delay in the terminal area due to excess leading/trailing aircraft wake vortex spacing. This analysis makes use of a large database of recorded traffic from early 2010 at several of the busiest Terminal Radar Approach Control Facilities (TRACONs) in the United States. To facilitate delay estimates, two arrival compression models are developed and applied to the recorded arrival traffic. A key feature of the compression modeling is the use of just two discrete points in the trajectory: TRACON entry and runway threshold crossing, eliminating the need for the resource intensive procedure of trajectory reconstruction. The analysis has two parts and each part focuses on two runways that are dedicated entirely to arrivals: KATL 27L and KDEN 35R. The first part is a sensitivity study exploring two strategies for compressing the arrivals: path reduction with original average true airspeeds and path reduction with (often times) faster average true airspeeds. This sensitivity study results in a range of delay savings on the order of tens of seconds per flight. The rest of the analysis uses the path compression model (original average true airspeeds), showing the uneven variation of daily delay savings at KATL 27L. Cumulative distribution functions capture the excess spacing reductions. They show a 10 percent increase (relative to the observed excess spacing) in arrivals landing with an excess spacing of 0.5 nmi or less at KATL 27L and a 25 percent increase at KDEN 35R.

Wold, G. R.

"AIRCRAFT CONTROL IN WAKE VORTEX WIND SHEAR"

NASA Langley Research Center, FAA/NASA Joint University Program for Air Transportation Research, 1993-1994, pp. 76-81

In the past, there have been several fatal incidents attributable to wake vortex encounters, involving both general aviation and commercial aircraft. In fact, the wake vortex hazard is the single dominant safety issue determining the aircraft spacing requirements at airports. As the amount of air traffic increases, the number of dangerous encounters is likely only to increase. It is therefore imperative that a means be found to reduce the danger. That is the purpose of this research: to use nonlinear inverse dynamic control methods in the design of an aircraft control system which can improve the safety margin in a wake vortex encounter.

Wolf, C. C., Merz, C. B., Richter, K. and Raffel, M.

"TIP-VORTEX DYNAMICS OF A PITCHING ROTOR BLADE-TIP MODEL"

AIAA Journal, Vol. 54, No. 10, October 2016, pp. 2947-2960.

The tip vortex of a finite rotor blade-tip model undergoing pitch oscillation is investigated by means of a wind-tunnel study. The motion and flow parameters as well as the model geometry were adapted to rotorcraft applications, including test cases with fully attached flow, light dynamic stall, and deep dynamic stall. High-speed particle image velocimetry was used to study the spatiotemporal behavior of the tip wake at different streamwise positions. Combined with surface pressure measurements, the data establish a connection between the sectional lift of the model and the vortex parameters (for example, swirl velocity and circulation), including dynamic phenomena like hysteresis and vortex breakdown during stalled flow conditions. For pitch oscillations below static stall limit, only small hysteresis effects were observed, and the vortex structure is like static reference measurements. Beyond static stall, the tip vortex retains its general structure in a time-averaged or phase-averaged frame, but the instantaneous flowfields reveal an increasing influence of turbulence. Dynamic stall cases exhibit a circulation overshoot beyond static levels during the upstroke and a disorganized and less-compact vortex structure during the downstroke.

Wolf, C. C., Merz, C. B., Richter, K. and Raffel, M.

"TIP VORTEX DYNAMICS OF A PITCHING ROTOR BLADE TIP MODEL"

AIAA Paper 2015-1492, January 2015, Kissimmee, FL.

The tip vortex of a finite wing undergoing pitch oscillations is investigated by means of a wind tunnel study. The motion and flow parameters as well as the model geometry were adapted to rotorcraft applications, including test cases with fully attached flow, light dynamic stall, and deep dynamic stall. High-speed Particle Image Velocimetry was used to study the spatio-temporal behavior of the tip wake at different streamwise positions. Combined to surface pressure measurements, the data establishes a connection between the sectional lift of the model and the vortex parameters (trajectory, swirl velocity, and circulation), including dynamic phenomena like hysteresis and vortex breakdown during stalled flow conditions. For pitch oscillations below static stall limit, only small hysteresis effects were observed, and the vortex structure is like static reference measurements. Beyond static stall, the tip vortex retains its general structure in a time- or phase-averaged frame, but the instantaneous flow fields reveal an increasing influence of turbulence. Dynamic stall cases exhibit a circulation overshoot beyond static levels during the upstroke and a disorganized and less compact vortex structure during downstroke.

Wolf, S.

"THE PILOTS VIEW ON WAKE VORTICES - CAPACITY VS. SAFETY"

Conference on Capacity and Wake Vortices, Imperial College of Science, Technology and Medicine, London, England, September 2001.

Capacity-problems in terms of 'movements per hour' are becoming a major driver for the economic performance of airports, ATM systems and airlines. The ICAO standard separation rules were developed in the early 70's, when the phenomenon of wake vortices made people aware of the danger when entering the wakes of a preceding aircraft. Today the values of these standard separations are discussed whether they are still adequate or not in specific situations. The dominant vortex hazard is the rolling moment induced on a directly following aircraft wing by the vortex motion. Because of the complexities of a vortex encounter, a simple parameter, the ratio of the maximum induced rolling moment to the maximum roll control authority of the aircraft, has generally been used to characterize the wake vortex hazard. The actual projects of a future VLTA (very large transport aircraft) are addressing the wake vortex problems during the whole design process as they want to prevent the birth of a 'super heavy' aircraft class thus neutralizing the capacity gain of large passenger decks by requiring additional track miles to separate the succeeding traffic. Since 1998 the IFALPA Wake Vortex policy has been passed as a result from many inputs from the national ALPA's. The topics that are addressed herein are: 1. a general commitment to serious efforts allowing a safe reduction of the standard wake-turbulence separation minima, 2. support for the results of international research activities contributing the development of any wake vortex warning/avoidance system, 3. the demand for airborne wake vortex detection systems, and 4. the demand for ground-based wake vortex advisory and warning systems.

Wong, C. C., Chan, P. W., Akaeda, K. and Mizuno, H.

"CALCULATION OF TURBULENCE INTENSITY BASED ON SPECTRUM WIDTH DATA OF A DOPPLER LIDAR"

Fourth Symposium on Lidar Atmospheric Applications, Paper P1.2, January 2009, Phoenix, Arizona.

The possibility of calculating EDR by using spectrum width data of a LIDAR with good digitization power for the spectral data (256-bit FFT) is demonstrated in this study based on the LIDAR system at Haneda Airport. The EDR values computed from this approach are found to have good correlation with those determined from structure function approach and the corrected spectrum width values. The spectrum width approach only requires the determination of one parameter, namely, the outer scale of turbulence, by iteration method in an implicit equation, instead of determining two parameters in the structure function approach. As such, this approach is computationally more efficient and thus more suitable for real-time implementation. For two cases of turbulent airflow associated with hangers at Haneda Airport, the turbulent wind areas are captured successfully in the EDR maps. Following the upgrade of the signal processors of the LIDARs at HKIA, a larger dataset would be used to evaluate the spectrum width approach of EDR computation.

Wong, O. D. and Komerath, N. M.

"TIP VORTEX FORMATION AND EVOLUTION TO THE NEAR WAKE OF A ROTOR IN FORWARD FLIGHT"

57th American Helicopter Society Forum, June 2001, Washington, DC, Vol. 1, pp. 193-204.

Realistic models of the formation, structure and evolution of tip vortices are essential to predict rotor blade aeroacoustics. Velocity measurements are reported here on tip vortex formation and evolution to the near wake from a teetering, untwisted, square-tipped, two-bladed NACA0015 rotor in low-speed forward flight. Given assured periodicity and appropriate measurement techniques, vortex formation results confirm observations made in the 1980s. Circumferential velocity profiles are observed as early as $x/c = 0.47$, growing in strength and core radius up to x/c of 1.06. The profiles of circumferential velocity manifest the rollup of discrete vortex filaments. The effect of seed particle dynamics on the accuracy of vortex measurements in the near wake is studied to verify accuracy. The wake structure and the tip vortex properties up to 488 degrees of wake age are presented. Harmonic variations are seen in the tip vortex core axial velocity. A strong spanwise velocity is seen on the pressure and suction sides of the blade. The core axial velocity appears to approach tip speed at origin, and the core circumferential velocity remains constant for a large distance after formation. The equations of motion describing seed particle motion in a 2D vortex were numerically integrated to quantify the velocity error of LDV measurements of the near-wake vortex characteristics due to seed particle dynamics. For a vortex strength of 0.75 meter squared per second typical of rotor tests at a tip Mach number of 0.15, the error in circumferential velocity error due to lag of particles between 1 and 5 microns, is seen to have an upper bound of 2 percent.

Wong, O., Mahalingam, R., Tongchipakdee, C. and Komerath, N. M.

"THE NEAR WAKE OF A 2-BLADED ROTOR IN FORWARD FLIGHT"

AHS Aeromechanics Specialist's Meeting, Nov. 2000, Atlanta, Georgia.

The velocity fields in the near wake and the blade tip flowfield of a square-tipped, rectangular planform, 2-bladed teetering rotor have been measured, in low-speed forward flight. A technique for establishing periodicity of the flowfield from laser velocimeter data is shown. The vortex trajectories and wake structure in low-speed forward flight are shown to a vortex age of 488 degrees. Harmonic variations of the axial velocity distributions in the tip vortices are observed. The issue of wake rollup and transition from near to far wake is addressed. It is seen that with periodicity ensured, phase-resolved measurements prove the persistence of the vortex to large ages, as well as the absence of turbulence inside the core of the rotor tip vortex.

Wong, W. K., Chan, P. W. and Li, C. M.

"VERIFICATION OF NWP TURBULENCE INTENSITY GUIDANCE USING EDDY DISSIPATION RATE FROM AIRCRAFT DATA"

24th Conference on Weather and Forecasting & 20th Conference on Numerical Weather Prediction, January 2011, Seattle, WA.

At the Hong Kong Observatory (HKO), the World Area Forecast System (WAFS) gridded forecast products from the two World Area Forecast Centres (WAFS) in London and Washington have been

made available to airlines and pilot users since August 2008 for evaluation. The WAFS trial gridded forecast products including clear-air turbulence (CAT) potential, in-cloud turbulence, icing and cumulonimbus clouds (CB) are provided up to T+36h at a forecast interval of 6 hours, based on the Unified Model (UM) of the UK Met Office (WAFS London) and the Global Forecast System (GFS) of NOAA/NCEP (WAFS Washington) respectively. This paper discusses the use of eddy dissipation rate (EDR) from commercial jets to verify the performance of NWP turbulence intensity products from the two WAFCs. Wind measurements recorded by flight data recorder are pre-processed by a band-pass filter algorithm to generate EDR. Contingency table approach is adopted to determine the hit, miss and false alarm of the clear air turbulence (CAT) potential from NWP models under different EDR thresholds. To assess the performance of model guidance, relative operating characteristic (ROC) curves are produced using different model CAT potential thresholds to determine the hit rate and false alarm. Additionally, the verification is applied to the turbulence intensity guidance from the Non-Hydrostatic Model (NHM), a new operational mesoscale NWP system in HKO. It is found that similar level of forecast skill on the moderate turbulence can also be obtained from NHM.

Wood, D. H.

"EFFECT OF TIP VORTEX GEOMETRY ON THE FLOW THROUGH THE BLADES OF HOVERING ROTORS"

Journal of Aircraft, Vol. 38, No. 3, May-June 2001, pp. 583-584.

It is concluded that the change in pitch of the tip vortex wake contraction is responsible for the average velocity through a hovering rotor being greater than the value from simple momentum theory. The effect of wake contraction is to reduce this discrepancy.

Wood, D. H.

"THE SECOND CURVATURE CORRECTION FOR THE STRAIGHT SEGMENT APPROXIMATION OF PERIODIC VORTEX WAKES"

Wind Energy Science, Vol. 3, 2018, pp. 345-352.

The periodic, helical vortex wakes of wind turbines, propellers, and helicopters are often approximated using straight vortex segments which cannot reproduce the binormal velocity associated with the local curvature. This leads to the need for the first curvature correction, which is well known and understood. It is less well known that under some circumstances, the binormal velocity determined from straight segments needs a second correction when the periodicity returns the vortex to the proximity of the point at which the velocity is required. This paper analyzes the second correction by modelling the helical far wake of a wind turbine as an infinite row of equispaced vortex rings of constant radius and circulation. The ring spacing is proportional to the helix pitch. The second correction is required at small vortex pitch, which is typical of the operating conditions of large modern turbines. Then the velocity induced by the periodic wake can greatly exceed the local curvature contribution. The second correction is quadratic in the inverse of the number of segments per ring and

linear in the inverse spacing. An approximate expression is developed for the second correction and shown to reduce the errors by an order of magnitude.

Wood, D. H. and Li, D.

"ASSESSMENT OF THE ACCURACY OF REPRESENTING A HELICAL VORTEX BY STRAIGHT SEGMENTS"

AIAA Journal, Vol. 40, No. 4, April 2002, pp. 647-651

The accuracy of representing a helical vortex, as found in the wakes of helicopters, wind turbines, and propellers, by a sequence of straight segments is considered. The accuracy is assessed by comparison with recent results for the induced velocity of a helix of constant pitch and radius. This comparison is motivated by the small values of the vortex pitch behind wind turbines and hovering rotors; small pitch leads to errors associated with the proximity of subsequent turns of the helix to the control point at which the velocity is required. Three cases are considered. The first, the velocity on the helix axis, has an analytic solution, which is used to demonstrate that the general accuracy of the straight segment approximation is second order, as has been found in previous comparisons with the velocity field of a vortex ring. For the second case, where the control point has the same radius as the vortex, the segments aligned with the control point are mainly responsible for the error. The error varies from first to third order as the number of segments per revolution of the helix is increased. Third, the self-induced velocity is determined to within an accuracy comparable with the effects of the vortex structure, of which little is presently known in general. The effects of vortex curvature are not significant and easily dealt with.

Wood, D. H. and Meyer, C.

"TWO METHODS FOR CALCULATING THE VELOCITIES INDUCED BY A CONSTANT DIAMETER FAR-WAKE"

J. Aircraft, Vol. 28, No. 8, August 1991, pp. 526-531

This paper describes two methods for calculating the velocities induced by the constant diameter helical vortices that occur in the far-wakes of helicopter rotors in hover or vertical flight, propellers, and horizontal-axis wind turbines. The velocities involve infinite integrals which, in general, cannot be integrated analytically. In the first method, each integral is evaluated numerically up to a finite limit and the remaining integral is approximated by an analytical function. The integrand of each function, or 'remainder' is found by summation over all of the vortices shed at the same radius. Numerical experiments show the remainders have a computational efficiency like those derived previously. The main features of the present remainders are simplicity and versatility. Furthermore, the remainders can replace numerical integration in some special cases. In the second method, the range of integration is made finite by transforming the integrand into one containing an infinite sum. The sum is approximated using the Euler-Maclaurin formula, and the resulting integral is evaluated numerically. The method is more cumbersome than the first but is robust, very accurate, and should be particularly useful at small vortex pitch.

Wood, V. T. and White, L. W.

"A NEW PARAMETRIC MODEL OF VORTEX TANGENTIAL-WIND PROFILES: DEVELOPMENT, TESTING AND VERIFICATION"

Journal of Atmospheric Science, Vol. 68, Issue 5, May 2011, pp. 990-1006.

A new parametric model of vortex tangential-wind profiles is presented that is primarily designed to depict realistic-looking tangential wind profiles such as those in intense atmospheric vortices arising in dust devils, waterspouts, tornadoes, mesocyclones and tropical cyclones. The profile employs five key parameters: maximum tangential wind, radius of maximum tangential wind, and three power-law exponents that shape different portions of the velocity profile. In particular, a new parameter is included controlling the broadly or sharply peaked profile in the annular zone of tangential velocity maximum. Different combinations of varying the model parameters are considered to investigate and understand their effects on the physical behaviors of tangential wind and corresponding vertical vorticity profiles. Additionally, the parametric tangential velocity and vorticity profiles are favorably compared to those of an idealized Rankine model and those of a theoretical stagnant core vortex model in which no tangential velocity exists within a core boundary and a potential flow occurs outside the core. Furthermore, the parametric profiles are evaluated against and compared to those of two other idealized vortex models (Burgers-Rott and Sullivan). The comparative profiles indicate very good agreements with low root-mean-square errors of a few tenths of a meter per second and high correlation coefficients of nearly one. Thus, the veracity of the parametric model is demonstrated.

Wood, V. T. and White, L. W.

"A NEW PARAMETRIC MODEL OF VORTEX TANGENTIAL-WIND PROFILE: TESTING AND VERIFICATION"

25th AMS Conference on Severe Local Storms, Poster Paper 10.12, Oct. 2010, Denver, CO.

The wind field around an intense atmospheric vortex such as a dust devil, tornado and mesocyclone can be accurately depicted using a parametric wind-profile model if the driving parameters are accurately determined. We developed a new parametric model to depict a realistic-looking tangential-wind profile that closely resembles that of any vortex. The profile employs five key parameters: maximum tangential wind, radius of maximum tangential wind and three power-law exponents that shape different parts of the velocity profile, including a new one that controls the broadly- or sharply-peaked profile in the annular zone of tangential velocity maximum. The objective of the paper is to test and verify the effectiveness and versatility of the new parametric wind-profile model by using numerical and analytical tangential wind measurements. The unsteady Burgers-Rott vortex model and the tornado numerical tangential-wind outputs of Trapp represent evolving simulated vortices. The analytical and numerical tangential speeds in the form of radial profiles radiating from the center of the vortex provide useful data and verify the parametric model.

Wood, W. D. and McWilliams, I. G.

"WAKE TURBULENCE DETECTION AND ECONOMIC IMPACT OF PROPOSED IMPROVEMENTS"

SAE Paper 77-0583, Washington, DC, May 1977

Increased separations of aircraft following heavy jets, which have been mandated because of the threat posed by aircraft trailing wake vortices, have aggravated the problem of air traffic delays at some of the busier airports. An extensive vortex measurement program at three major airports has provided the data base for the design of a Vortex Advisory System which will permit reduction of the vortex-imposed separations under certain measurable wind conditions. This system which promises to effect an appreciable reduction in traffic delay is currently undergoing testing at Chicago's O'Hare International Airport.

Wood, W. D., editor

"FAA/NASA PROCEEDINGS WORKSHOP ON WAKE VORTEX ALLEVIATION AND AVOIDANCE"

FAA-RD-79-105, October 1979, DOT Transportation Systems Center, Cambridge, MA

This document is a record of the joint FAA/NASA Workshop on Wake Vortex Alleviation and Avoidance conducted at the DOT Transportation Systems Center, November 28-29, 1978. The workshop was sponsored by the Federal Aviation Administration to apprise the appropriate specialists of the state of the art and to formulate program recommendations for wake vortex alleviation at the source, for wake avoidance systems, and for operations, and safety regulations.

Wood, W. D., Hallock, J. N. and Spitzer, E. A.

"WAKE VORTEX PROGRAM"

IEEE Northeast Electronics Research and Engineering Meeting, Boston, MA, 1973

The objective of the DOT/TSC wake vortex program is the increase in airport capacity without compromising the safety of operations. The paper shows how vortex dynamics and sensors coupled with user requirements lead to the description of three basic vortex avoidance systems: a warning system, an advisory system, and an Air Traffic Control integrated system which satisfies both the safety and the capacity aspects.

Woodfield, A. A.

"ROLL AND LIFT DISTURBANCES DUE TO WAKE VORTICES"

Report 9504, July 1995, Chief Scientist's Division, Civil Aviation Authority, London, UK.

This report presents a model of the effect on an aircraft of encountering a vortex wake. Methods for calculating the ratios of the induced rolling moment to the aircraft's roll control capability and of the lift change to the aircraft's weight are given. It is recommended that these methods should be used as the basis for a model of dynamic motion during a complete encounter and recovery that can be used to quantify hazards.

Woodfield, A. A.

"REVIEW OF PILOT REPORTS OF WAKE VORTEX ENCOUNTERS FOLLOWING IMPLEMENTATION OF RVSM IN EUROPEAN AIRSPACE, JANUARY to OCTOBER 2002"

Report No. 200301, February 2003, Woodfield Aviation Research, Bedford, U.

EuroControl implemented Reduced Vertical Separation Minima (RVSM) in January 2002, and from that time until October 2002 some 26 reports of possible wake vortex encounters were received. Ten of these events occurred below RVSM airspace and a further 5 were clearly encounters with Clear Air Turbulence (CAT). The remaining 11 are probably wake vortex encounters, but in 3 of these one of the aircraft involved is climbing or descending and thus the encounter is not a consequence of the implementation of RVSM. One of these climb/descent events is below RVSM flight levels. This leaves 8 events where a wake vortex was encountered under RVSM conditions, and 2 under climb/descent conditions at RVSM heights. The number of RVSM operations in European airspace over the period is not known to the author, but it is likely that they are at least in the tens of thousands per month. Thus, the reporting rate is very small. The report reviews all 10 wake vortex encounters above FL245, but clearly separates the events with both aircraft cruising with RVSM vertical separation (1,000 ft.) from those involving climbs or descents.

Woodfield, A. A.

"EN-ROUTE ENCOUNTERS WITH WAKE VORTICES, AND THE IMPLICATIONS OF REDUCED VERTICAL SEPARATION MINIMA (RVSM)"

Report No. 9901, March 1999, Woodfield Aviation Research, Bedford, United Kingdom.

Wake vortices are shed downstream by all aircraft and can be a potential hazard in en-route flight conditions as well as in the terminal area close to the ground. Introduction of Reduced Vertical Separation Minima (RVSM) bring aircraft closer together and it is important to assess whether or not this will significantly increase the risk of a hazardous encounter with wake vortices. Operations under RVSM in Oceanic airspace provide some practical experience with which to make an initial assessment of the likely effects of introducing RVSM in the more complex environment of European space. Heavy or Medium aircraft changing flight level within less than 2-3 minutes and through that of an encountering aircraft generate the greatest risk of a hazardous encounter. Data from reports to the UK CAA and NATS of wake vortex encounters in Oceanic airspace under RVSM are studied, and some earlier data from en-route wake vortex encounters. It is noted that there were no significant wake vortex encounter incidents in the first nine months of RVSM operations over the North Atlantic, which is estimated to cover about 100,000 flights. However, there were several nuisance encounters and a contingency procedure was introduced to allow lateral upwind track offsets to move an aircraft safely away from continuing nuisance encounters with a wake. This seems to have eliminated wake vortex incident reports, although there is no doubt that nuisance encounters still occur. Relevant features in European airspace that do not occur in Oceanic airspace are a wider mix of aircraft sizes, a greater number of aircraft changing flight levels, the presence of traffic on reciprocal tracks in airways, the

intersection of airways, and the presence of up and down draughts at high altitudes because of winds passing over mountain ranges. These effects have been considered and it is concluded that the presence of mountain ranges and the wider mix of aircraft sizes will increase the probability of encountering wake vortices with RVSM compared with Oceanic airspace, but the encounters should remain a nuisance rather than a hazard. When wake vortex encounters occur and persist then a change of flight level, heading, or a track offset of 1 n.m. will usually prevent further encounters.

Woodfield, A. A.

"UPDATE OF WAKE VORTEX DECAY AND MOTION PREDICTIONS AND THEIR IMPLICATIONS FOR CRUISE CONDITIONS"

Report No. 200102, August 2001, Woodfield Aviation Research, Bedford, United Kingdom

Assessments of potential changes in the risk of hazardous wake vortex encounters in cruise from reducing vertical separation minima (RVSM) require methods for estimating wake vortex vertical motion and decay. An empirical method developed by Greene in 1986 has been used for some years, but there has been concern that some of the assumptions and empirical constants may not be appropriate for extending estimates to high altitude cruise conditions. The author of this report has derived a similar method called the Unified Vortex Mass (UVM) method. Comparison of estimates from the UVM method and a small sample of encounter reports shows good agreement with the decay profile derived from that suggested by Sarpkaya and measurements of wake vortex condensation trails by Bisgood. Overall, the vortex descent at a potentially hazardous vorticity strength is somewhat greater than that estimated by Greene's method. For the largest aircraft considered (B-747-400), vortex descent increases from 410 ft. to 510 ft., but this is not sufficient to change the conclusion from previous analysis that the introduction of RVSM is unlikely to increase the probability of hazardous wake vortex encounters. With the UVM method it is now possible to estimate the effects of vertical draughts on vortex motion. Modest downdraughts will increase the probability of encountering strong vortices, although the main hazard from significant downdraughts will be collision hazards following involuntary height changes, which can occur because aircraft are often operating near their performance limits in cruise.

Wooller, J. and Firmin, M. C. P.

"AN EXPERIMENTAL INVESTIGATION INTO THE DETERMINATION OF LIFT FROM WAKE TRAVERSES AT SUPERSONIC SPEEDS"

C. P. No. 801, 1965, Aeronautical Research Council, Great Britain

Two theoretical results are derived by an approximate method for relating the lift on an object to the properties of the flow in its wake. An experimental investigation was devised, firstly to compare the flow properties with those indicated by horseshoe-vortex and linearized theories, and secondly, to compare the lift derived from those properties with the lift measured by a conventional strain-gauge balance. Results are presented which indicate a maximum difference of 6% between the

measurements for the lift, provided the traverses enclose the complete viscous wake, but improved theory and apparatus are necessary if the lift is to be obtained more precisely by wake traverse methods.

Wren, J. E. and Baxa, Jr., E. G.

"CONSTANT FALSE ALARM RATE DETECTION OF WAKE VORTICES WITH APPLICATION TO A PULSED DOPPLER LIDAR SYSTEM"

Proceedings 1999 Conf. on Radar Into the Next Millenium., Piscataway, N. J., pp. 90-95

A 2-micron pulsed Doppler lidar system is being evaluated as a means of remotely detecting wingtip-induced vortices, i.e., wake vortices, in the approach corridor at an airport runway. The lidar system is placed beside the runway approach corridor and scanned in elevation. A structured signal processor estimates the Doppler spectra of the time sampled lidar return. A constant false alarm rate (CFAR) algorithm is applied to field test data and used to estimate the Doppler velocity profile of the cross section of space scanned by the lidar system and the size and strength of the wake vortices. The resulting CFAR detector exhibits the ability to distinguish between different aircraft sizes by the vortex strength.

Wren, J. E. and Baxa, Jr., E. G.

"CONSTANT FALSE ALARM RATE DETECTION OF WAKE VORTICES WITH APPLICATION TO A PULSED DOPPLER LIDAR SYSTEM"

IEEE National Radar Conference - Proceedings, 1999, pp. 90-95

In this paper, a 2-micron pulsed Doppler lidar system is being evaluated as a means of remotely detecting wingtip-induced vortices, i.e., wake vortices, in the approach corridor at an airport runway. The lidar system is placed beside the runway approach corridor and scanned in elevation. A structured signal processor estimates the Doppler spectra of the time sampled lidar return. A Constant False Alarm Rate (CFAR) algorithm is applied to field test data and used to estimate the Doppler velocity profile of the cross section of space scanned by the lidar system and the size and strength of the wake vortices. The resulting CFAR detector exhibits the ability to distinguish between different aircraft sizes by the vortex strength.

Wright, C.

"EXPERIMENTAL STUDY OF THE STRUCTURE AND DEVELOPMENT OF A WINGTIP VORTEX IN THE NEAR-FIELD"

ICAS-2002-8.2.3, Toronto, Canada, September 2002.

The purpose of the wind tunnel measurements was to study the effect of a flat wing end-cap and a round end-cap on the near field of the vortex pair. A NACA 0015 wing at 4-, 8-, and 12-degree angle of

attack was used. The scaled Reynolds number was approximately 1 million. Flow visualization (laser light and smoke) and velocity measurements (triple sensor hot wire probe) were employed.

Wright, C. T.

"EXPERIMENTAL STUDY OF THE STRUCTURE OF A WINGTIP VORTEX"

MS Thesis, 2000, Utah State University, Logan, UT.

A complete look at the near-field development and subsequent roll-up of a wingtip vortex from a NACA 0015 wing section is investigated. Two separate but equally important surveys of the vortex structure in the region adjacent to the wingtip and approximately one chord length downstream of the trailing edge are performed. The two surveys provide qualitative flow visualization and quantitative velocity measurement data. The near-field development and subsequent roll-up of the vortex structure are strongly influenced by the angle-of-attack and the end-cap treatment of the wing section. The velocity field near the wingtip of the NACA 0015 wing section was measured with a triple-sensor hot wire probe and compared to flow visualization images produced with titanium tetrachloride smoke injection and laser illumination. The flat end-cap results indicate the formation of multiple, relatively strong vortex structures as opposed to the formation of a single vortex produced with the round end-cap. The multiple vortices generated by the flat end-cap are seen to rotate around a common center in a helical pattern until they eventually merge into a single vortex. Compared to a non-dimensional loading parameter, the results of the flow visualization data show a 'jet-like' axial velocity profile for loading parameter values on the order of 0.1 and a 'wake-like' profile for much lower loading parameter values.

Wu, J. and Menon, S.

"NUMERICAL STUDIES OF NEAR-FIELD PLUME-VORTEX INTERACTIONS"

AIAA Paper No. 1998-2902, Albuquerque, NM, June 1998

In this study, fluid mixing and chemical reactions in the near-field wake of an aircraft has been investigated. The plume-vortex regime is studied using a 3D parallel LES code. Simulations of engine plume interaction with the wing-tip vortex of B737 and B747 have been carried out and some comparisons with data have been used to demonstrate the ability of the LES method. Inclusion of detailed gas phase kinetics and simple heterogeneous processes have been carried out to evaluate the effect of turbulent mixing on the chemical processes in the plume-vortex regime. Finally, to determine the impact of temporal assumptions (often used in such flow simulations) comparison with spatial simulations are carried out. Many features of the computed flow field show reasonable agreement with experimental data. The entrainment of the engine plumes into the wing-tip vortex and also the partial detrainment of the plume were numerically captured and analyzed. The impact of fluid mechanics on the chemical process has been estimated. Results indicate that a significant difference between spatial and temporal simulation exists (especially in the predicted SO₃ concentration). This has important implications for the prediction of sulfuric acid aerosols in the wake and may partly

explain the discrepancy between past numerical studies and the data. Analysis of the results also show that spatial simulation is more suitable for the near-field interaction process. For example, it was determined that detrainment (observed in the B747 contrail) was only captured using the spatial model.

Wu, J. C.

"THEORY FOR AERODYNAMIC FORCE AND MOMENT IN VISCOUS FLOWS"

AIAA Journal, Vol. 19, No. 4, April 1981, pp. 432-441.

A general theory for aerodynamic forces and moments, developed through a rigorous analysis of the viscous flow equations, is presented. General formulas relating aerodynamic forces and moments to rates of change of vorticity moments in the fluid and the solid regions are presented. Analytical results for several problems are presented to demonstrate the application of the theory in interpreting complex aerodynamic phenomena and in computational fluid dynamics.

Wu, J. C. and Singh, J.

"UNSTEADY AERODYNAMICS OF NON-RIGID BODIES -- A NOVEL APPROACH"

AIAA Paper No. 1988-0565, Reno, NV, January 1988

A procedure to evaluate unsteady aerodynamic forces on non-rigid lifting bodies undergoing prescribed time-dependent motions is described. The kinematic aspect of the incompressible viscous flows in the form of an integral representation for the velocity vector is utilized to obtain an explicit expression for the surface vortex sheet representing the vorticity contents of the boundary layers. Knowing the surface vortex sheet strength and the strengths and locations of the wake vortices, a general theory of aerodynamics is then used to evaluate the unsteady aerodynamic forces.

Wu, J. C., Hackett, J. E. and Lilley, D. E.

"A GENERALIZED WAKE-INTEGRAL APPROACH FOR DRAG DETERMINATION IN THREE-DIMENSIONAL FLOWS"

AIAA Paper No. 1979-0279, New Orleans, LA, January 1979

A generalized theory relating the drag on a three-dimensional lifting body in a wind tunnel to properties of the vortical wake downstream of the body is presented. In the well-known theory of Betz, the profile drag is expressed as a wake integral, i.e., an integral over only the vortical wake region of a downstream section. The present theory shows that, under quite general circumstances, the induced drag is also determined accurately by a wake integral. The theory offers some insight to the interplay between the drag components and the wake characteristics. Results of an exploratory experimental study are presented in the paper. They show that wake measurements at sections near the lifting body can determine the induced drag with good accuracy.

Wu, J. C., Wang, C. M. and McAlister, K. W.

"WAKE-INTEGRAL DETERMINATION OF AERODYNAMIC DRAG, LIFT AND MOMENT IN THREE-DIMENSIONAL FLOWS"

AIAA Paper No. 2002-0555, Reno, NV, January 2000.

New wake-integral expressions for the determination of aerodynamic load on finite wings and rotors are established using a vorticity-moment theorem. Compared to previous wake-integral expressions based on the momentum theory, the new expressions connect the wake flow properties more directly to the aerodynamic load. They offer enhanced physical understanding of the flow mechanisms responsible for the production of aerodynamic force and moment and are simpler and more efficient to use. Wind-tunnel experiments are performed to validate the wake-integral expressions for the thrust and the torque on rotors in slow climb. A three-dimensional particle-image velocimetry system is used to obtain velocity values in the near-wake of a model rotor. Thrust and torque values determined using the wake data are presented and compared with balance-measured values.

Wu, J. M. and Gilliam, Jr., F. T.

"A FLOW VISUALIZATION STUDY OF THE EFFECT OF WING-TIP JETS ON WAKE VORTEX DEVELOPMENT"

In Flow Visualization III, Proceedings of the Third International Symposium, Ann Arbor, MI, September 1983, Hemisphere Publishing Corp., 1985, pp. 387-391

The use of discrete wing-tip jets to improve the wing performance and to modify the tip vortex roll up has been investigated. A complicated three-dimensional vortex interaction in the vicinity of the wing tip flow field becomes more clear through the flow visualization study in a water tunnel. The existence of many induced secondary vortices was discovered. This finding leads to a theoretical model for analyzing the interacting vortices flow field. Flow visualization also helped in pointing out the direction for future study.

Wu, J. M., Vakili, A. D. and Gilliam, F. T.

"AERODYNAMIC INTERACTIONS OF WINGTIP FLOW WITH DISCRETE WINGTIP JETS"

AIAA Paper No. 1984-2206, Seattle, WA, August 1984

Wind and water tunnel data and calculations of the effects on wing aerodynamic performance by the presence of discrete wing tip jets are reported. A NACA 0012-64 airfoil equipped for interchangeable tips that provided various blowing configurations was used in the tests. Data were gathered on forces and moments at three spanwise locations and dye injection provided flow visualization. A relatively small jet had a large effect on the spanwise pressure distribution. Three separate types of boundary vortices were produced by the tip jets: spin-off vortices extending into the potential flow region, auxiliary vortices parallel to the main flow, and entrained vortices in the jet and wingtip vortices. Wake

vortices were dispersed while total circulation increased, thereby effectively enhancing the aspect ratio and overall wing performance.

Wu, J. M., Vakili, A. D., Shi, Z. and Mo, J. D.

"PHENOMENA OF DISCRETE WINGTIP JETS"

Report 88-06, August 1988, University of Tennessee Space Institute, Tullahoma, TN.

Detailed flow phenomena of discrete wingtip jets blowing from a rectangular wing with squared edges and round tips are investigated in the water- and wind-tunnel experiments. Phenomena on a single asymmetric jet blowing from a flat-plate in crossflow were incorporated into the present wingtip jet study. The local flow field perturbation introduced by the tip jet blowing closely resembles that of the asymmetric jet from the flat-plate. The wingtip jet has influenced the global surface pressure distribution over the wing and improved the lift loading. A simple mathematical model is developed for practical calculation of wing loading.

Wu, J. Z. and Wu, J. M.

"GUIDING PRINCIPLES FOR VORTEX FLOW CONTROLS"

AIAA Paper No. 1991-0617, Reno, NV, January 1991

In the practice of vortex flow controls, the most important factor is that the persistency and obstinacy of a concentrated vortex depend on its stability and dissipation. In this paper, the modern nonlinear stability theory for circulation-preserving flows is summarized, and the dissipation for general viscous flows is analyzed in terms of the evolution of total enstrophy. These analyses provide a theoretical base for understanding relevant physics of vortex flows, and lead to some guiding principles and methods for their controls. Case studies taken from various theoretical and/or experimental works of vortex controls, due to the present authors as well as others, confirm the feasibility of the recommended principles and methods.

Wu, J.-Z., Xiong, A.-K. and Yang, Y.-T.

"AXIAL STRETCHING AND VORTEX DEFINITION"

Physics of Fluids, Vol. 17, March 2005, pp. 038108-1 to 038108-4

Four existing invariant criteria for defining a vortex are diagnosed analytically and demonstrated by the Burgers and Sullivan vortices. Two of the criteria are found disqualified as generally applicable, and one underestimates the core radius. The diagnosis leads to a general requirement for any possible criterion: it should be able to identify the vortex axis and allow for arbitrary axial strain.

Wu, S., Liu, B. and Liu, J. L.

"AIRCRAFT WAKE VORTEX MEASUREMENT WITH COHERENT DOPPLER LIDAR"

27th ILRC International Laser Radar Conf., July 2015, New York City, NY.

Aircraft vortices are generated by the lift-producing surfaces of the aircraft. The variability of near-surface conditions can change the drop rate and cause the cell of the wake vortex to twist and contort unpredictably. The pulsed Coherent Doppler Lidar Detection and Ranging is an indispensable access to real aircraft vortices behavior which transmitting a laser beam and detecting the radiation backscattered by atmospheric aerosol particles. Experiments for Coherent Doppler Lidar measurement of aircraft wake vortices has been successfully carried out at the Beijing Capital International Airport (BCIA). In this paper, the authors discuss the Lidar system, the observation modes carried out in the measurements at BCIA and the characteristics of vortices.

Wu, S., Yin, J., Li, R., Wang, X., Liu, B. and Liu, J.

"OBSERVATIONS AND ANALYSIS OF TURBULENT WAKE OF WIND TURBINE BY COHERENT DOPPLER LIDAR"

27th ILRC International Laser Radar Conf., July 2015, New York City, NY.

Turbulent wake of wind turbine will reduce the power output of wind farm. The access to real turbulent wake of wind turbine blades with different spatial and temporal scales is provided by the pulsed Coherent Doppler Lidar (CDL) which operates by transmitting a laser beam and detecting the radiation backscattered by atmospheric aerosol particles. In this paper, the authors discuss the possibility of using lidar measurements to characterize the complicated wind field, specifically wind velocity deficit by the turbine wake.

Wu, S., Zhai, X. and Liu, B.

"CHARACTERIZATION OF AIRCRAFT DYNAMIC WAKE VORTICES AND ATMOSPHERIC TURBULENCE BY COHERENT DOPPLER LIDAR"

19th Coherent Laser Radar Conference (CLRC), Paper Th5, June 2018, Okinawa, Japan.

Wake vortex are large rolling air masses generated by aircraft because of lift. The behavior of that wake vortex is a major issue in aeronautical research. They are strongest and most hazardous on congested airfields during take-off and landing, i.e. near the ground. It is held that serious interactions between wake vortex and the ground can significantly affect the evolution of wake vortex, thus making them difficult to predict. To investigate the real approach to mitigate wake vortex using 1.55-micron coherent Doppler lidar and to study the wake vortex near ground effect (NGE), the wake vortex observation project was carried out during Jan-Mar 2017 at Beijing International Airport (BCIA). This paper focuses on the NGE analyze based on 2017 BCIA experiment (2017BCIAE) observation.

Wu, S., Zhai, X., Liu, B. and Liu, J.

"CHARACTERIZATION OF AIRCRAFT DYNAMIC WAKE VORTICES AND ATMOSPHERIC TURBULENCE BY COHERENT DOPPLER LIDAR"

28th International Laser Radar Conference, June 2017, Bucharest, Romania, published in EPJ Web of Conferences, Vol. 176, 2018, pp. 06001-1 to 06001-4.

Field observations for the wake vortices by Coherent Doppler Lidar (CDL) have been carried out at the Beijing International Airport (BCIA) and Tianjin Binhai International Airport (TBIA) to investigate the wake vortices evolution characteristics and the near-ground effect. This paper introduces the dynamic wake vortices and atmospheric turbulence monitoring technique, successfully demonstrating that the CDL can capture the key characteristics of wake vortices in real-time, including wake vortices intensity, spatial-temporal evolution and so forth.

Wu, S., Zhai, X., Liu, B., Feng, C. and Liu, J.

"WIND TURBINE WAKE CHARACTERIZING USING COHERENT WIND LIDAR"

18th Coherent Laser Radar Conference, June 2016, Boulder, CO.

Wind power is growing fast as one of the most promising renewable energy sources. When the wind turbine generator (WTG) extracts power from the wind, the wake evolves and leads to a considerable reduction in the efficiency of the actual power generation. The wake effect also leads to the increase of fatigue loads that reduce the life time of WTGs. In this work, a Pulsed Coherent Doppler Lidar (PCDL) is used to characterize the WTG wakes, which has high updating rate of 4 Hz and variable spatial resolution from 15 to 60 m. Field experiments were performed in the onshore and offshore wind parks from 2013 to 2015. Techniques based on a single Doppler Lidar were employed for elucidating main features of turbine wakes, including velocity deficit, wake dimension, velocity profile, 2D wind vector, turbulence dissipation rate and turbulence intensity under different conditions of surface roughness.

Wu, Y., Hu, Y., Xu, S., Li, J. and Dai, D.

"DESIGN OF AIRPORT WAKE VORTEX MONITORING SYSTEM BASED ON 1.5-MICRON PULSED COHERENT DOPPLER LIDAR"

Optoelectronics Letters, Vol. 7, No. 4, July 2011, pp. 298-303.

To shun the vortex hazard, the airport wake vortex monitoring system based on 1.5-micron pulsed coherent Doppler lidar is designed successfully in this paper. Based on realistic analytical model, the wake vortex generated by airbus A340 under typical flight condition is simulated. Then the principle of airport wake vortex monitoring is introduced, and the work flow of the monitoring system is also presented. Moreover, based on the mechanism of vortex coherent detection and typical system parameters, both detection SNR and detection precision are obtained through numerical simulations. When the system outputs 2J energy, the coherent detection SNR at 10 km distance is up to 23.452, and detection precision can reach 0.328 m/s. With the wake vortex monitoring experiment of A340, some

vortex parameters are estimated. Due to these results comparatively coinciding with the previous simulation conclusions, the ability of Doppler lidar for full-scale wake vortex characterization and real time measurement is demonstrated. The study shows that the wake vortex detection based on 1.5-micron pulsed coherent Doppler lidar has the advantage of high accuracy and far distance, and the designed airport wake vortex monitoring system has proved to be effective and feasible, which has significant development and application prospect in the aspect of assuring flight security and increasing airport capacity.

Wu, Y.-H., Hu, Y.-H., Dai, D.-C., Xu, S.-L. and Li, J.-M.

"RESEARCH ON THE TECHNIQUE OF AIRCRAFT WAKE VORTEX DETECTION BASED ON 1.5 MICRON DOPPLER LIDAR"

Acta Photonica Sinica, Vol. 40, No. 6, June 2011, pp. 811-817.

To shun the wake vortex hazard and assure the flight security, the technique of wake vortex detection by Lidar was studied. The basic principle of wake vortex detection was introduced, and both the detection mode and the system parameters of Lidar were also given. Based on the designed scheme of wake vortex detection by Lidar, the relationships between Doppler spectrum value and the parameters of aircraft type, flight and environment were studied. The radial velocity distribution law of wake vortex was acquired, and the Doppler spectrum model of its laser echo was built. Moreover, the optimal parameters estimation algorithm was selected for wake vortex characterization. Based on the performed wake vortex detection experiment of A340, both the feasibility of wake vortex detection by Lidar and the validity of parameters estimation algorithm of wake vortex were verified. The research results show that the laser echo created of wake vortex is inversely proportional to the cube of radial velocity, but is directly proportional to the square of circulation. [In Chinese.]

Wunenburger, R., Andreotti, B. and Petitjeans, P.

"INFLUENCE OF PRECESSION ON VELOCITY MEASUREMENTS IN A STRONG LABORATORY VORTEX"

Experiments in Fluids, Vol. 27, 1999, pp. 181-188.

A strong laboratory vortex is generated in a cylindrical cell using a rotating disk and stretched by pumping the fluid out through a hole in the center of the top of the cell. The velocity field is measured by means of laser Doppler anemometry and Doppler ultrasonic anemometry which are both non-intrusive methods. The vortex exhibits a slight precession which induces temporal fluctuations of the velocity at the measurement point. Due to the centrifugal force, the tracers concentrate in a tubular region around the vortex, leading to spatial variations of the measurement counting rate. Under these two effects, the probability density function of the one point velocity exhibits a strong non-Gaussian behaviour. In order to access the details of the velocity profile of the vortex in its own system of reference, the influence of the vortex precession, of the spatial variations of the concentration in tracers and of the intrinsic measurement dispersion is investigated and a model is proposed. It allows

to recover statistically the characteristics of the vortex and to deduce the trajectory of its centre from the instantaneous velocity profiles.

Wurzbach, R.

"THE VELOCITY FIELD BEHIND A LIFT GENERATING WING OF FINITE SPAN"

Zeitschrift fur Flugwiss, Vol. 5, No. 12, December 1957, pp. 360-365

When calculating the velocities induced by a wing of finite span, the process of rolling-up the vortex sheet formed behind the wing, and its displacement are considerably simplified. For estimating the field of induced velocities, a method is given which considers the rolling-up and the displacement of the vortex sheet. [In German.]

Wussow, S., Sitzki, L. and Hahm, T.

"3D-SIMULATION OF THE TURBULENT WAKE BEHIND A WIND TURBINE"

Journal of Physics, Conference Series, Vol. 75, 2007, pp. 1-8.

The paper relates to the simulation of the airflow around a wind turbine (WT) of the type ENERCON E66 with emphasis on the turbulent wake. The simulations were undertaken with the Computational Fluid Dynamics software ANSYS FLUENT 6.3 using the LES technique for turbulence modeling. It is the aim of the work to capture the full three-dimensional turbulent flow behind a WT in a sufficient spatial and temporal resolution to generate information for wind loads of WTs in wind farm configuration. This information shall help to optimize wind farm layouts in the future. Using an incoming wind field that matches the requirements of the IEC-61400 for wind fields used in load calculations it was possible to simulate a full meandering turbulent wake. The turbulent features of the WT wake could be reproduced with numerical methods not using further assumptions but solely based on the WT geometry and the solution of the governing physical equations.

Wynanski, I.

"METHOD AND APPARATUS FOR DELAYING THE SEPARATION OF FLOW FROM A SOLID SURFACE"

US Patent 5,209,438, May 1993

An active perturbation-producing element on the solid surface is driven to induce oscillations in the boundary layer of the fluid stream about an axis substantially perpendicular to the solid surface, to enhance the mixing of the boundary layer in the fluid stream. The method is particularly applicable for increasing the lift of a wing, but may also be used for increasing the divergence angle of a diffuser.

Wynnyk, L., Lunsford, C. R., Tittsworth, J. A., and Pressley, S.

"DEVELOPMENT OF APPROACH AND DEPARTURE AIRCRAFT SPEED PROFILES"

Journal of Aircraft, Vol. 54, No. 1, January-February 2017, pp. 94-103.

Information on the suggested aircraft speeds can be obtained from flight manuals, but the actual airspeeds flown by an aircraft will vary based on the aircraft landing weight, airport altitude, wind conditions, and other Air-Traffic-Control related factors. The recent advent of new tools and an abundance of new, highly accurate aircraft surveillance data have enabled a reevaluation of past airspeed profile assumptions. The resulting analysis provides a stronger representation for airspeeds flown on final approach and initial departure by the aircraft types comprising a large percentage of U.S. Instrument Flight Rules operations. Furthermore, the time to fly is calculated to determine how long it takes the trailer aircraft to fly the distance to the point where the leader generates a particular portion of the wake. Although this work is performed to provide improved inputs for Recategorization Phase II analyses, the airspeed profiles derived from aircraft surveillance data will also be valuable to other Air Traffic Control applications (such as the Advanced Traffic Proximity Alert, the Interval Management-Paired Approach, Time-Based Flow Management, and the Integrated Departure Arrival Capability) that require accurate knowledge of how aircraft approach and departure airspeeds vary in actual operations.

Xie, Y., Shortle, J. and Choroba, P.

"QUANTITATIVE ESTIMATION OF WAKE VORTEX SAFETY USING THE P2P MODEL"

6th USA/Europe ATM R&D Seminar, April 2005, Paper 57, Baltimore, MD

Wake vortex encounter risk is a major safety issue in aircraft final approach phase. The evaluation of the risk is crucial when the industry takes the effort to reduce aircraft spacing for the purpose of capacity gain. This paper proposes a hybrid analytical method to assess the wake vortex encounter risk during the final approach phase. The hybrid method uses probabilistic method to calculate the risk based on the probabilistic distributions of aircraft positions and vortex characteristics obtained from Monte Carlo simulations. The proposed method will be more computational efficient than pure simulations to evaluate the probability of a rare event, such as a serious vortex encounter. In addition, it can provide insights about risk distributions with respect to time and location. The estimation given by the model is conservative, which provides effective safety margin to the risk evaluation in a highly stochastic environment.

Xin, J., Chen, R. and Li, P.

"TIME-STEPPING FREE-WAKE METHODOLOGY FOR ROTOR FLOW FIELD SIMULATION IN GROUND EFFECT"

Aircraft Engineering and Aerospace Technology, Vol. 87, No. 5, 2015, pp. 418-426.

The purpose of this paper is to provide an approach to predict rotor thrust and hub moments under in ground effect (IGE) in transient flight. Target of the research is developing a new integrated methodology that can be applied in the simulation of rotor flow field IGE. Free-wake model and panel method are two methods used to predict ground influence on rotor flow field. However, these methods can result in unphysical phenomena, such as wake vortex moving below the ground during simulation and fluctuation taking place on vortices near the ground, which is named noise problem. Thus, a new tactic called 'constant volume rectification' is developed to rectify the unreal vortex location, and a third-order time-stepping algorithm called CB3D (Center difference and Backward difference 3rd-order scheme with numerical Dissipation) with strengthened stability is proposed to replace the existing second-order time-stepping algorithm CB2D (Center difference and Backward difference 2nd-order scheme with numerical Dissipation) to inhibit the development of discrete error. The new free-wake model is effective and stable in predicting the characteristics of the rotor flow field in steady and transient flights under IGE. The newly developed CB3D scheme is more stable and more suitable for wake prediction of rotor under IGE than the CB2D scheme. At different advance ratios, the predicted flow regimes of recirculation and ground vortex agree well with the test images. In the accelerating condition, the predicted variations of rotor thrust and hub moments with advance ratios are consistent with the corresponding experimental results. It is found that the slow movement of wake geometry with advance ratio in the accelerating condition is the cause of the delay in the variation tendency of rotor forces compared to that in steady condition.

Xin, J., Li, P. and Chen, R.

"FREE-WAKE ANALYSIS OF HOVERING ROTOR IN GROUND EFFECT"

Acta Aeronautica et Astronautica Sinica, Vol. 33, No. 12, December 2012, pp. 2161-2170.

A free-wake based model with fine convergence is developed to predict the wake geometry of a hovering rotor operating in ground effect (IGE). The vortex line is discretized into straight-line filaments, and the influence of the ground is modeled using a surface panel method. Since earlier studies show it is hard for the free-wake to converge when the rotor is hovering at a low height, the work of this study incorporates several modification measures to improve the convergence of the model, such as rectifying the wake vortices below the ground plane proportionally and distributing the ground panels circularly, which reduced the calculation amount of the model at the same time. The model is validated with prediction instances in which the rotor is placed at different heights. A comparison of the determined wake geometries with experimental data shows good agreement and proves the proposed model possesses good accuracy. [In Chinese.]

Xu, J., Ning, S. A., Bower, G. and Kroo, I.

"AIRCRAFT ROUTE OPTIMIZATION FOR FORMATION FLIGHT"

Journal of Aircraft, Vol. 51, No. 2, March-April 2014, pp. 490-501.

We quantify the fuel and cost benefits of applying extended formation flight to commercial airline operations. Central to this study is the development of a bi-level, mixed-integer real formation flight optimization framework. The framework has two main components: 1) a continuous-domain aircraft mission performance optimization and 2) an integer optimization component that selects the best combination of optimized missions to form a formation flight schedule. The mission performance reflects the effects of rolled-up wakes, formation heterogeneity, and formation-induced compressibility. The results show that an airline can use formation flight to reduce fuel burn by 5.8 percent or direct operating cost by 2.0 percent in a long-haul international schedule. The savings increase to 7.7 percent in fuel or 2.6 percent in cost for a large-scale, transatlantic airline alliance schedule. These results include the effects of a conservative fuel reserve for formation flight. Sensitivity studies show that a modest reduction in the cruise Mach number may be sufficient to manage the impact of formation-induced compressibility effects on system-level formation flight performance. We demonstrate that the potential savings from extended formation flight (an operational improvement using existing aircraft) can approach those claimed for advanced vehicle technologies and unconventional configurations.

Xu, S.-L., Hu, Y.-H.. and Zhao, N.-X.

"EXTRICATION OF WAKE VORTEX PARAMETERS BASED ON LIDAR ECHO"

Acta Photonica Sinica, Vol. 42, No. 1, January 2013, pp. 54-58.

To realize the monitoring of the aircraft wake vortex effectively, solve the puzzles of flight safety and runway capacity limitation, an algorithm of wake vortex parameter extrication based on Lidar echo is proposed. The physical model of circulation and radial velocity distribution is studied, and the structure of wake vortex is described. Based on the features of the vortex parameters, the flowchart of parameter extrication is given, as echo signal processing for noise reduction, threshold selection for velocity envelopes to resolve the velocity distribution and parameter (core radius, core position, circulation) extrication. Moreover, the calculation example of extrication algorithm is carried out by taking a certain type of aircraft for example which is compared with the model simulation. The experimental result verifies the effectiveness of the extrication algorithm. [In Chinese.]

Xu, X. and Chan, P. W.

"RETRIEVAL OF 3D WIND FIELD FROM LIDAR VELOCITY DATA"

14th Coherent Laser Radar Conference, July 2007, Snowmass, Co.

The Hong Kong Observatory (HKO) operates a Doppler LIDAR at the Hong Kong International Airport (HKIA) for airflow monitoring and windshear alerting. Complex airflow occasionally occurs in the vicinity of HKIA due to terrain disruption. To better visualize the wind in the airport area, 2D wind retrieval based on the LIDAR's radial velocity measurement is conducted. This paper is an extension of the work by using a more sophisticated technique to retrieve the 3D wind field around HKIA.

Xu, X., Zhao, H., Wang, Z.

"OVERVIEW OF WAKE VORTEX SEPARATION REDUCTION SYSTEMS"

Acta Aeronautica et Astronautica Sinica, Vol. 31, Issue 4, 2010, pp. 655-662

Flight delay is nowadays one of the most critical curbing factors in aviation industry. While the efficiency of air transportation is improved by air traffic flow management, massive research work on wake vortex separation reduction is also performed by researchers all around the world. One of the technologies developed to date is to modify flight procedure aiming at the reduction of the wake vortex separation of closely spaced parallel runways; and another is to build wake turbulence prediction models to anticipate the dissipation and transportation of wake vortex. Thus, a wake turbulence separation consultative matrix is calculated to acquire more landing and take-off slots. The wake vortex separation reduction systems can alleviate flight delay and increase terminal capacity. They are assorted into two categories according to different principles adopted in design, i.e., wake vortex separation system based on offset approach procedure and wake vortex separation system based on dynamic prediction. The theory, algorithm and components of each system are thoroughly analyzed. The performance of the systems is compared and the advantages and drawbacks of each system are discussed.

Xue, Y., Xu, H.-J. and Wang, X.

"BUILD PROBABILITY DISTRIBUTION MAPS OF FLIGHT RISK DURING WAKE ENCOUNTERING"

Journal of Aircraft, Vol. 52, No. 3, May-June 2015, pp. 805-818.

Under the background of increasing wake vortex problems, flight risk probabilities during wake encountering are evaluated using complex system theory and multivariate extreme value theory. First, three-dimensional extreme flight parameters required for assessing the risk are extracted using Monte Carlo simulation. The one-dimensional extreme parameters are verified to have the same distribution type of thick tail as the test data. Second, the four adaptive weight parameters copula is proposed for modeling the distributions of three-dimensional extreme parameters. The result of the fitting test shows the four adaptive weight parameters copula has higher accuracy than the other cupola. Third, the flight risk probability in every corresponding grid point is evaluated by taking the four adaptive weight parameters copula to model the extreme parameters in the wake field. At last, the visual two-dimensional and three-dimensional distribution maps of flight risk probability are built, and the topology characteristics of risk distributions at different stages are analyzed. The maximum flight risk probability during wake encountering is about 13.5 percent. The work is an effective complement to the aircraft system safety assessment method. It also has some reference values for research on wake navigation control, risk aversion, airport safety interval improvement, environmental risks visualization, and so on.

Yamada, K. and Suzuki, K.

"DYNAMICAL SYSTEM ANALYSIS ON THE ONSET OF RECIRCULATING FLOW REGION ASSOCIATED WITH VORTEX BREAKDOWN"

AIAA Paper 2016-4347, June 2016, Washington, DC.

In this study, the onset of axisymmetric vortex breakdown in a closed cylinder is extensively investigated numerically by solving the incompressible axisymmetric Navier-Stokes equations. A longitudinal vortex tube, which is generated around the center axis of the cylinder, goes to burst after the radial expansion of the vortex tube and the appearance of a pair of stagnation points on the axis, by which a recirculating flow region is bounded. Such process is examined from the aspects of the velocity profile along the axis and the eigensystem of the velocity gradient tensor around the stagnation points, varying the Reynolds number and the aspect ratio of the cylinder.

Yamaguchi, Y., Arima, T., Obayashi, S. and Nakahashi, K.

"SIMULATION OF AIRCRAFT WAKE VORTEX USING PRESSURE-BASED UNIFIED NUMERICAL APPROACH FOR INCOMPRESSIBLE AND COMPRESSIBLE FLOWS"

AIAA Paper No. 2004-0077, Reno, NV, January 2004

A wake vortex simulation using CFD methodology based on a new pressure-based unified approach is presented. A numerical method is developed to attain calculation for both in incompressible and compressible flows regime with a low numerical diffusive property and for high prediction accuracy of pressure gradient. This scheme is constructed by splitting the full Navier-Stokes equation into an advection role by velocity and a propagation role by acoustic wave. In the advection phase, concept of the advective upwind splitting method (AUSM) is adapted to non-conservative advection equations. For the acoustic phase, SMAC-like Poisson's equation is derived to reduce a numerical error. Newly developed scheme shows good agreement except strong shock capturing capability for validation problems including incompressible, compressible and vortical flow calculations. Finally, wake vortex simulation for NACA0012 rectangular wing is investigated. The computation results show availability of new approach for wake vortex flow predictions.

Yamamoto, A., Nakamura, D., Mizuki, S. and Tsujita, H.

"DETAILED FLOW VISUALIZATION AROUND COMPLEX BODIES"

Proceedings of 9th International Symposium on Flow Visualization, Edinburgh, Scotland, August 2000, pp. 327-1-327-8

Flows around geometrically complex bodies, such as whole airplane models and sports car models, have been measured in a small wind tunnel especially designed for detailed and precise measurements with a full-automatic controlled traverse gear. Lots of data were obtained using a micro five-hole Pitot tube to make clear the flow mechanisms around the bodies with help of computer graphic software for three-dimensional flow analyses. Pressure and velocity fields were visualized in the three-dimensional space, vortex and even separated/reverse flow regions were detected from the resultant visualization

pictures. The present technique gives 'quantitative' visualization of the flows around complex bodies and enables us to make 'invisible' quantities clearly visible. Three-dimensional streamlines or particle paths were also obtained from experimental data.

Yamasuge, H., Yoshikawa, E., Ushio, T., Ishii, S., Aoki, M. and Hashimoto, K.

"EXPERIMENTAL VERIFICATION OF WIND LIDAR WITH LONG-DURATION FREQUENCY-MODULATED PULSE"

19th Coherent Laser Radar Conference (CLRC), Paper P17, June 2018, Okinawa, Japan.

In our previous research, a new wind lidar which accomplishes high power and high range resolution by transmitting laser pulses with long duration and frequency modulation was proposed. In the proposed wind lidar, analytical performance evaluation under ideal conditions indicated that accuracies of wind ranging and velocimetry increases in proportion to the square root of pulse duration. In this research, we investigated accuracies of modulated pulse shaping that is one of the issues to realize the proposed wind lidar. We developed an experimental system which directly returns generated laser pulses to its receiver, and digitally measured the returned waveform. Although, in the returned signal, the returned waveform is distorted compared to its ideal waveform, the result of matched filter processing showed sufficient performances that the mainlobe width was almost maintained, and peak power was reduced very little by -0.3 dB as compared with the ideal waveform.

Yamauchi, G. K., Johnson, W. and Wadcock, A. J.

"VORTEX WAKE GEOMETRY OF A MODEL TILT ROTOR IN FORWARD FLIGHT"

American Helicopter Society International Meeting on Advanced Rotorcraft Technology and Life Saving Activities, Tochigi, Japan, November 2002

The vortex wake trajectory from one rotor of a 0.25-scale V-22 tiltrotor model was measured for four test conditions in the NASA Ames 40- by 80-Foot Wind Tunnel. Vortex wake images were acquired using a laser light sheet and video camera. Wake trajectories were constructed by extracting vortex positions from the video images. Wake trajectories were also calculated using the comprehensive analysis CAMRAD II. Measured and calculated wake geometries exhibit similar trends when advance ratio is varied at fixed thrust or when thrust is varied at fixed advance ratio.

Yamauchi, G. K., Burley, C. L., Mercker, E. and Pengel, K.

"FLOW MEASUREMENTS OF AN ISOLATED MODEL TILT ROTOR"

55th Annual Forum, American Helicopter Society, Montreal, Canada, May 1999

Wake measurements on the advancing side of a 0.25-scale V-22 isolated tilt rotor are presented and discussed. Three-dimensional wake geometry data were obtained using the Laser Light Sheet (LLS) technique. The position of wake segments relative to the rotor blade were acquired for a range of

thrust and shaft angles. The rotation sense of the wake segments was determined. The lower thrust condition generated negative tip loading over a larger portion of the rotor disk than the higher thrust condition. At a higher thrust condition for the same shaft angle, the number of observed negative circulation vortices decreased. Two-dimensional velocity measurements were obtained using the Particle Image Velocimetry (PIV) technique. Three methods for averaging the PIV velocity data are discussed. Two of the methods account for vortex wander; both methods, however, require further refinement to determine which method provides more accurate results. The third method, which does not account for vortex wander, should only be used to obtain general features of the flow. For the vortices examined, approximately 100 PIV samples were determined to be sufficient for computing the average vortex core size and core circulation. The core size and core circulation of the negative vortices were smaller than the positive circulation vortices. The core tangential velocity appears to have a nearly linear relationship to the core size for the vortices examined. The fraction of total circulation in the core for both negative and positive vortices was found to be consistent with the Scully and Oseen vortex models.

Yang, F. B., Xue, X. Y., Zhang, L. and Sun, Z.

"NUMERICAL SIMULATION AND EXPERIMENTAL VERIFICATION ON DOWNWASH AIR FLOW OF SIX-ROTOR AGRICULTURAL UNMANNED AERIAL VEHICLE IN HOVER"

International Journal of Agricultural & Biological Engineering, Vol. 10, No. 4, 2017, pp. 41-53.

Recently, multi-rotor unmanned aerial vehicle (UAV) becomes more and more significantly irreplaceable in the field of plant protection against diseases, pests, and weeds of crops. The easy takeoff and landing performance, hover function and high spraying efficiency of UAV are urgently required to spray pesticide for crop timely and effectively, especially in dispersed plots and hilly mountains. In such situations, the current researches about UAV spray application mainly focus on studying the influence of the UAV spraying parameters on the droplet deposition, such as operation height, operation velocity and wind velocity. The deposition and distribution of pesticide droplets on crops which depends on installation position of nozzle and airflow distribution characteristics of UAV are directly related to the control effect of pesticide and crop growth in different growth periods. As a preliminary step, this study focuses on the dynamic development law and distribution characteristics of the downwash air flow for the SLK-5 six-rotor agricultural UAV. Based on compressible Reynolds-averaged Navier-Stokes (RANS) equations with an RNG k- ϵ turbulence model and dynamic mesh technology, the efficient three-dimensional computational fluid dynamics (CFD) method was established to analyze the flow field distribution characteristics of UAV in hover. Then the unsteady interaction flow field of the wing was investigated in detail. The downwash wind speed of the marked points for the SLK-5 UAV in hover was also tested by weather tracker. It was found that the maximum velocity value of the downwash flow was close to 10 m/s; the z-direction velocity was the main body of the wind velocity in the downwash airflow, and the comparison of the wind velocity experiment test and simulation showed that the relative error was less than 12% between the experimental and simulated values of the z-direction velocity at the marked points. Then the flow characteristics of the longitudinal and cross section were analyzed in detail, the results obtained can be used as a reference for drift and sedimentation studies for multi-rotor unmanned aerial vehicle.

Yang, K. and XU, S.

"WING TIP VORTEX STRUCTURE BEHIND AN AIRFOIL WITH FLAPS AT THE TIP"

Science China Physics, Mechanics and Astronomy, Vol. 54, No. 4, April 2011, pp. 743-747.

In this work, the wing tip vortex structure behind a NACA 0015 airfoil with and without small flaps was studied using a Particle Image Velocimetry (PIV) system. The experiment was carried out in a low-speed wind tunnel with a test section of 0.5m x 0.5m. The Reynolds number defined by the chord length of the wing (C) was 81000. The angle of attack was fixed at 10 degrees. The PIV measurements were made from 0 to $2C$, measured from the trailing edge of the model. The dihedral angle of three flaps was -15, 0 and 15 degrees, respectively. Compared with the clean model, the one with three flaps significantly changed the wing tip vortex structure, the vorticity, and the core of the wing tip vortex. The occurrence of three flaps decreased the gradient of pressure on the two sides of the wing tip, which depressed wing tip vortex formation to some extent. Vortices shed from three flaps influence the evolution of the wingtip vortex generated by the base airfoil. The interaction of those vortices resulted in a weakening of the wing tip vortex.

Yang, S., Luo, S., Liu, F. and Tsai, H.-M.

"EULER SOLUTIONS OF FLOW AROUND A RECTANGULAR WING WITH SQUARE TIP"

AIAA Paper No. 2007-896, Reno, NV, January 2007

Low speed flows about a high-lift rectangular wing with square lateral tip are computed by a three-dimensional compressible Euler flow solver. Flow separation around the square tip of the wing is studied. The flow is, otherwise, attached to the surface of the wing. The pressure distributions over the upper and lower surfaces of the wing, especially on the outer portion of the wing and the generation and evolution of the tip vortices in the near field of the wing are computed by the Euler method and validated by a comprehensive wind-tunnel test data in the literature. The effects of the wind-tunnel wall are not considered in the computations.

Yang, X. and Domaradzki, J. A.

"LARGE EDDY SIMULATIONS OF DECAYING ROTATING TURBULENCE"

Physics of Fluids, Vol. 16, No. 11, November 2004, pp. 4088-4104

Large eddy simulations of homogeneous isotropic turbulence subjected to system rotation were performed using the truncated Navier-Stokes method. In the method the Navier-Stokes equations are solved through a sequence of direct numerical simulation runs and a periodic processing of small scales to provide the necessary dissipation. The method is evaluated by comparing simulation results with theoretical analysis, direct numerical simulations, as well as with other large eddy simulation results. Obtained results demonstrate several advantages of the method over traditional large eddy simulations

models. The method captures important features of rotating turbulence: the energy decay is inhibited, the energy spectrum departs from the classical k to the $-5/3$ form, and initially isotropic turbulence becomes anisotropic. For increasing rotation rate three distinct regimes are observed. At low rotation rates, the influence of rotation is weak and flow behaves like for nonrotating cases. At intermediate rotation rates strong coupling between rotation and nonlinear interactions has a significant influence on turbulence. At high rotation rates viscous effects dominate over nonlinear effects. Furthermore, for high Reynolds numbers, small Rossby numbers, and large elapsed time, the k to the -3 energy spectrum is observed due to the anisotropy identified by various indicators, rather than k to the -2 form found under the assumption of isotropy.

Yang, Z., Ozbay, A., Sarkar, P. and Hu, H.

"AN EXPERIMENTAL INVESTIGATION ON THE WAKE INTERFERENCE OF WIND TURBINES SITED OVER COMPLEX TERRAINS"

AIAA Paper No. 2012-1069, January 2012, Nashville, TN.

An experimental study was conducted to investigate the interferences of wind turbines sited over hilly terrains to elucidate underlying physics to explore/optimize design paradigms of wind turbines sited over complex terrains for higher power yield and better durability. The experiments were conducted in a large wind tunnel with wind turbine models sited over a flat terrain (baseline case) and a 2D-ridge with non-homogenous atmospheric boundary layer winds. In addition to measuring dynamic wind loads (both forces and moments) and the power outputs of the wind turbine models, a high-resolution digital Particle Image Velocimetry system was used to conduct detailed flow field measurements to quantify the flow characteristics of the surface winds and wake interferences among multiple wind turbines over flat (baseline case) and complex terrains. The detailed flow field measurements were correlated with the wind load measurements and power outputs of the wind turbine models to elucidate the underlying physics associated with turbine power generation and fatigue loads acting on the wind turbines.

Yang, Z., Sankar, L. N., Smith, M. J. and Bauchau, O.

"RECENT IMPROVEMENTS TO A HYBRID METHOD FOR ROTORS IN FORWARD FLIGHT"

Journal of Aircraft, Vol. 39, No. 5, September-October 2002, pp. 804-812

A hybrid Navier-Stokes/full potential solver has been developed for the efficient prediction of three-dimensional unsteady viscous flow phenomena that occur over helicopter rotors in forward flight. The method combines a Navier-Stokes analysis near the blade, modeling the viscous flow and near wake with a potential flow analysis in the far field, modeling inviscid isentropic flow. A grid motion module has been developed to account for the blade motion and elastic deformations. Free and prescribed wake models have been developed to account for the tip vortex effects once the vortex leaves the viscous flow region and enters the potential flow region. Sample results are presented for a two-

bladed AH-1G rotor in descent and for a UH-60A rotor in high-speed forward flight. Comparisons with experiments, flight test data, and other numerical simulations are given.

Yang, Z., Sarkar, P. and Hu, H.

"VISUALIZATION OF THE TIP VORTICES IN A WIND TURBINE WAKE"

Journal of Visualization, Vol. 15, 2012, pp. 39-44

In the present study, an experimental study was conducted to characterize the formation and the evolution of the helical tip vortices and turbulent flow structures in the wake of a horizontal axis wind turbine model placed in an atmospheric boundary layer wind. A high-resolution particle image velocimetry system was used to make detailed flow field measurements to quantify the time evolution of the helical tip vortices in relation to the position of the rotating turbine blades in order to elucidate the underlying physics associated with turbine power generation and fatigue loads acting on the wind turbine.

Yao, W. and Chen, Z.

"TWO DIMENSIONAL VORTICES MERGING ANALYSIS"

AIAA Paper No. 2007-4366, Miami, FL, June 2007.

This paper focuses on the interaction of co-rotating vortices, like those in the near-wake of transport aircraft. The fundamental process of vortex merging is analyzed and modeled in detail in a two-dimensional context. Vortex merging criterion and its physical origin was also discussed. Finally, bifurcation theory was used to determine the merging criterion. Numerical simulation of vortex merging was studied through N-S equation and the LES turbulence model was employed; spectral method was used to initialize the flow field. In the temporal direction, the 2nd order method was accepted. The distance between two vortices cores at different time stage was also given in present paper, the result was in good agreement with DNS result. The process of vortex merging was divided into four stages. The duration of four stages were also given in present paper. The so-called 'rebound' phenomenon was described and analyzed theoretically. The relationship between duration and Reynolds number was discussed. At last, the final flow field characteristic was predicted, including vortex core size characteristic.

Yao, Z. X. and Liu, D. D.

"VORTEX DYNAMICS OF BLADE-BLADE INTERACTION"

AIAA Paper No. 1994-0737, Reno, NV, January 1994.

A time domain method has been developed for treatments of vortex dynamics in all classes of blade-blade interaction problems. A new 'vortex impingement' condition is introduced to the discrete vortex tracking scheme and was found most effective in handling the vortex-airfoil interaction, the wake-airfoil

interaction (WAI), and the blade-blade interaction (BBI) problems. Various computed examples are presented for different classes of interaction problems ranging from single airfoil to airfoils in tandem in indicial or oscillatory motions. Present results are verified with all classical solutions and are found in good agreement with almost all existing solutions. From the present BBI study, it is concluded that any front blade movement will induce a strong interaction between the wake and the rear airfoil; hence, it alters drastically the lift response and the wake structure. Any rear blade movement only induces a weak interaction; hence, it remains comparatively ineffective to the response. Comparative study of WAI and BBI results indicates that the airfoil interference effect is relatively insignificant as opposed to that of the wake-airfoil interaction.

Yao, Z. X., Garcia-Fogeda, P., Liu, D. D. and Shen, G.

"VORTEX/WAKE FLOW STUDIES FOR AIRFOILS IN UNSTEADY MOTIONS"

AIAA Paper No. 1989-2225, Seattle, WA, August 1989

A time-domain method has been developed to account for vortex-airfoil-wake interaction problems. The present method is based on a high-order panel scheme on the airfoil coupling with the discrete vortex tracking technique for treatments of the wake and assigned free vortex. Computation examples include complete checks of classical problems, high angle of attack histogram, and various vortex-airfoil interaction problems. New results for the impulsively-started airfoils in tandem are also presented. The present method is found to be a robust one in handling the vortex-airfoil-wake interaction problems. Finally, issues involving conservation of vorticity condition and vortex models will be discussed.

Yaras, M. I.

"EFFECTS OF ATMOSPHERIC CONDITIONS AND GROUND PROXIMITY ON THE DYNAMICS OF AIRCRAFT WAKE VORTICES: A STUDY OF THE 1994-1995 MEMPHIS FIELD MEASUREMENTS"

XXIII General Assembly, European Geophysical Society, Nice, France, April 1998.

This paper studies aircraft wake data acquired by the MIT Lincoln Laboratory and NASA Langley Research Center at the Memphis, TN international airport during December 1994 and August 1995. The objective is to identify the dominant mechanisms affecting the transport and decay of aircraft wake vortices. Specifically, the effects of atmospheric stratification, wind shear, atmospheric turbulence and ground proximity on the far-wake development are examined. The wake-vortex trajectories are observed to closely follow the ideal descent path under calm and near-neutral atmospheric conditions and away from the ground. Increased variability in the vertical wake trajectory is noted under high ambient turbulence (normalized turbulence levels more than 0.5) with observations of descending as well as rising vortices for the same turbulence energy. Interaction of the wake vortices with nonuniform ambient vorticity associated with a ground-jet crosswind profile is observed to arrest their vertical descent leading to a rebound. No discernable changes are observed in wake-vortex transport and decay over a normalized Brunt-Vaisala frequency range of 0.2 to 0.5. Wake-vortex rebound due to

viscous ground interaction is observed to occur about one time unit after the arrest of the initial vertical descent. For wake vortices generated sufficiently close to the ground, the rebound is immediate. An effect of stratification on the rebound process is not observed over a range of normalized Brunt-Vaisala frequencies of 0.07 to 0.35. Furthermore, neither winds aligned with the wake axis nor wind shear in this direction appear to influence the rebound process.

Yaras, M. I.

"NUMERICAL SIMULATIONS OF AIRCRAFT WAKE-VORTEX DYNAMICS IN NONUNIFORM WINDSHEAR AND GROUND PROXIMITY"

AIAA Paper No. 2002-0940, Reno, NV, January 2002

The work presented herein examines the interaction of aircraft wake vortices with nonuniform ambient shear in proximity of the ground. The investigation is based on two- and three-dimensional numerical simulations using a grid-based Reynolds-averaged Navier-Stokes solver. The simulations are tailored to establish the extent of simplifications in mathematical modeling that can be realized while maintaining acceptable accuracy. The results are intended to provide the ground work for the development of real-time algorithms that may be used at airports in dynamic spacing of aircraft during landing and take-off. Through comparison with field data as well as simulations based on a one-equation turbulence model, the assumption of a constant eddy viscosity is shown to be adequate for modeling the turbulent diffusion of wake vortices in low-turbulence ambient conditions. Nonlinear interactions are demonstrated in the instance of simultaneous influence of ambient shear and ground proximity on the wake-vortex dynamics. Furthermore, neither axial motion within the core of the wake vortices nor nonuniform headwind shear are shown to have significant influence on the kinematics of the wake/crosswind-shear interaction, lending support for two-dimensional modeling of this flow if three-dimensional instability effects are accounted for separately. Finally, the results help to establish the levels of accuracy and resolution of wind measurements that are required for reliable prediction of wake-vortex dynamics in nonuniformly sheared ambient conditions.

Yaras, M. I.

"EFFECTS OF ATMOSPHERIC CONDITIONS AND GROUND PROXIMITY ON THE DYNAMICS OF AIRCRAFT WAKE VORTICES: A STUDY OF THE 1994-95 MEMPHIS FIELD MEASUREMENTS"

TP-13372E, March 1999, Carleton University, Ottawa, Ontario

To identify the mechanisms affecting the transport and decay of aircraft wake vortices, the effects of atmospheric stratification, wind shear, atmospheric turbulence and ground proximity were examined using the data collected at Memphis International Airport in December 1994 and August 1995. Of the atmospheric parameters considered, large-scale atmospheric turbulence and non-uniform wind shear were observed to substantially influence the wake transport and decay. The extent of rebound following viscous interaction with the ground was like published results of laboratory tests conducted at much lower Reynolds numbers.

Yarmus, J., Burnham, D. C., Wright, A. and Talbot, T.

"AIRCRAFT WAKE VORTEX TAKEOFF TESTS AT O'HARE INTERNATIONAL AIRPORT"

DOT/FAA/RD-94-25, August 1994, Volpe National Transportation Systems Center, Cambridge, MA.

Three wake vortex measurement systems (anemometer, acoustic doppler, and laser doppler) were used to collect wake vortex data from aircraft departing Runway 22L at Chicago's O'Hare airport for nine months in 1980. The data were analyzed to determine vortex decay and vortex transport probabilities. The results support the classification of all B-707 and DC-8 aircraft in the large wake vortex class. The acoustic doppler system was found to be significantly more sensitive than the ground anemometer system to vortices transported long distances laterally by a crosswind. The most efficient lateral transport was noted for crosswinds greater than seven knots. The horizontal and vertical ground wind signatures of a wake vortex are compared.

Yaroshevsky, V. A.

"THE CALCULATION OF VORTEX WAKE KINETIC ENERGY AND THE EFFECT OF CIRCULATION DISTRIBUTION ON SOME CHARACTERISTICS OF WAKE"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 26-33

The vortex wake rolls up into two parallel vortex cords at a short distance (about 10-15 wingspans downstream the aircraft). Considering the well-known assumption that the rotational kinetic energy of the wake in the nearfield is produced by the work of induced drag, it is possible to calculate the size of so-called core radius of each vortex. A very simple law has been found for the accurate calculation of this kinetic energy. The paper analyzes the effect of circulation distribution on some important characteristics of vortex wake: core radius, maximum induced velocity in the near field, rate of vortex-pair height loss, mean time of vortex-pair life, rate of vortex core growth.

Yasue, M., Vehlow, C. A. and Ham, N. D.

"GUST RESPONSE AND ITS ALLEVIATION FOR A HINGELESS HELICOPTER ROTOR IN CRUISING FLIGHT"

Fourth European Rotorcraft and Powered Lift Aircraft Forum, Paper No. 28, September 1978, Stresa, Italy, pp. 28-1 - 28-39.

The vertical gust response and its alleviation for hingeless helicopter rotor blades in cruising flight is studied theoretically and experimentally. An evaluation is performed of the effectiveness of torsional stiffness variation in conjunction with chordwise center-of-gravity shift in alleviating the blade flapping response to decrease the root bending moment. The theoretical analysis utilizes the equations of motion of hingeless rotor blades exposed to vertical gusts in forward flight for the flapping, lagging, and elastic and rigid pitch degrees of freedom. The equations include the effect of steady-state deflections

in the trim conditions and various hingeless rotor configurations such as precone, droop and torque offset as well as chordwise center-of-gravity shift and aerodynamic center offset. The experimental program involves the wind tunnel tests of a five-foot diameter rotor subject to a sinusoidal waveform gust. Testing involves variation of the blade chordwise center-of-gravity location, the blade torsional stiffness, rotor advance ratio, and vertical gust frequency.

Yates, J. E.

"INTERACTION WITH AND PRODUCTION OF SOUND BY VORTEX FLOWS"

AIAA Paper No. 77-1352, Atlanta, Georgia, April 1977.

A general theory of aeroacoustics of homentropic fluid media is presented. The definition of sound (unsteady compressible flow) and the concept of Bernoulli enthalpy are the fundamental building blocks of the theory. It is proved that a Coriolis acceleration is necessary to obtain a transfer of energy from the vortical to the acoustic mode. With the Lighthill hypothesis the theory is formally equivalent to the Lighthill or Ribner theory in the low Mach number limit. The present theory is complete in that all the basic aeroacoustic interactions can be investigated, in particular, the excitation of a fluid flow by sound. The interaction of sound with vortex flows is studied in detail. A formula for vortex core scattering is derived with a plane wave analysis. A general theory of acoustic interaction with multiple weakly interacting line vortices is presented. The theory is applied to estimate the interference noise between an engine and an aircraft vortex wake. For the DC-9 in a standard take-off configuration the interference noise is estimated to be 3 or 4 dB at the engine peak Strouhal number. The noise produced by a corotating vortex pair is calculated with the present theory. For low Mach number (M less than 0.1) the sound power varies as M to the 7th power in accordance with known results for compact 2-D flows. For M greater than 0.1 but less than 0.3 the power radiated is 10 to 15 dB less than the compact M to the 7th power law, even though the basic source is still quadrupole. For M greater than 0.3 higher order multipoles contribute to the sound power.

Yates, J. E.

"APPLICATION OF THE BERNOULLI ENTHALPY CONCEPT TO THE STUDY OF VORTEX NOISE AND JET IMPINGEMENT NOISE"

NASA CR-2987, April 1978, Aeronautical Research Associates of Princeton, Princeton, NJ.

A complete theory of aeroacoustics of homentropic fluid media is developed and compared with previous theories. The theory is applied to study the interaction of sound with vortex flows, for the DC-9 in a standard take-off configuration. The maximum engine-wake interference noise is estimated to be 3 or 4 dB in the ground plane. It is shown that the noise produced by a corotating vortex pair departs significantly (10 to 15 dB reductions) from the compact M scaling law for eddy Mach numbers (M) greater than 0.1. An estimate of jet impingement noise is given (~ 10 dB increase in sound power) that is in qualitative agreement with experimental results. The increased noise results primarily from the nonuniform acceleration of turbulent eddies through the stagnation point flow. It is shown that the

corotating vortex pair can be excited or de-excited by an externally applied sound field. The model is used to qualitatively explain experimental results on excited jets.

Yates, J. E.

"CALCULATION OF INITIAL VORTEX ROLL-UP IN AIRCRAFT WAKES"

J. Aircraft, Vol. 11, No. 7, July 1974, pp. 397-400.

The initial in-plane acceleration of a vortex sheet in two-dimensional incompressible flow is calculated. The theory is used to estimate the strength and location of the discrete vortices that roll-up behind an aircraft wing. Numerical results are presented for a C-141 takeoff and a DC-9 landing configuration. The results verify a hypothesis of Donaldson for estimating the strength and location of the discrete vortices that is required in a Betz-type roll-up calculation. The present theory also provides an estimate of the relative rates of vortex roll up.

Yates, J. E.

"A STUDY OF SCATTERING, PRODUCTION, AND STIMULATED EMISSION OF SOUND BY VORTEX FLOWS"

NASA Contractor Report 3139, May 1979, Aeronautical Research Associates of Princeton, Princeton, NJ.

The basic theory of aeroacoustics of homentropic fluid media is applied to the problem of sound scattering, production, and stimulated emission. A general theory of scattering from low speed three-dimensional vortex flows is presented. Specific results are given for the horseshoe vortex and vortex ring. The noise of an elementary corotating vortex pair in various flows is calculated. It is shown that a potential flow and shear flow can substantially increase the basic pair noise. Small reverse shears can annihilate vortex pairs and eliminate the pair noise mechanism. The pair results are used to explain qualitatively the operation of noise suppression devices. The stimulated emission of a single vortex pair and four and six vortex arrays is demonstrated. The results for six vortices illustrate how external pure tones can amplify the broadband noise of a jet in agreement with recent experimental evidence.

Yates, L. A. and Chapman, G. T.

"STREAMLINES, VORTICITY LINES, AND VORTICES"

AIAA Paper No. 1991-0731, Reno, NV, January 199.

The properties of vortical flows are studied using both theoretical analysis and computational flow fields. The consequences of two definitions of the vortex core, a minimum in the streamline curvature and a maximum in the normalized helicity, are examined. Analysis indicates that several criteria must be met if the cores defined by these two methods are to coincide. In certain regions of the flow, computational flow fields indicate that these two definitions are coincident, that the velocity and vorticity fields are aligned at the core, and that extrema in the velocity magnitude, vorticity magnitude, pressure, and density occur at the core.

Ye, Q.-Y. and Chu, C. K.

"UNSTEADY EVOLUTIONS OF VORTEX RINGS"

Phys. Fluids, Vol. 7, No. 4, April 1995, pp. 795-801

Unsteady evolutions of vortex rings with linearly distributed vorticity and various core parameters are considered in an unbounded, inviscid fluid. The instability of a Norbury vortex with a moderate core thickness parameter is also investigated. Contour integral expressions based on the Biot-Savart law for the velocity field induced by a vortex ring are derived. Numerical results show that all vortex rings except the Norbury vortices will undergo an unsteady evolution process to reach an asymptotic state. The process may be roughly divided into two major stages: initial large deformation stage and later asymptotic oscillating stage. Vortex filamentation is often observed during the first stage. In the second stage, the vortex oscillates periodically with nearly constant amplitude; its core closely resembles a Norbury vortex having the same circulation and impulse, but the dynamic properties and kinetic energies are different.

Yeh, D. T. and Plotkin, A.

"VORTEX PANEL CALCULATION OF WAKE ROLLUP BEHIND A LARGE ASPECT RATIO WING"

AIAA Paper No. 1985-1561, Cincinnati, OH, July 1985

A higher order (linear vortex) panel method is used to calculate the three-dimensional wake rollup behind large aspect ratio symmetric wings in steady inviscid incompressible flow. Triangular shaped panels are chosen to increase the geometric flexibility of the wake sheet. The wing spanwise circulation distribution is obtained from lifting line theory and the wake geometry is then evaluated in an iterative fashion by satisfying conservation of circulation, flow tangency as well as zero pressure jump for all wake panel surfaces in the near wake region (two spans in length). The far wake is modeled by straight semi-infinite vortex filaments that are in the uniform stream direction. Numerical results are shown to compare favorably with those in the literature. The capability of the method to model a rectangular wing with a deflected flap is also studied.

Yemenici, O., Uzol, N. S. and Uzol, O.

"INVESTIGATION OF ROTOR-ROTOR INTERACTIONS FOR TWO HELICOPTERS IN FORWARD FLIGHT USING FREE-VORTEX WAKE METHODOLOGY"

AIAA Paper No. 2010-4558, July 2010, Chicago, Illinois.

This paper presents an investigation of the aerodynamic interactions between two UH-1H helicopter rotors in forward flight. The wake flow structure and performance characteristics of the rotors are investigated when the rear rotor is operating within the wake of the front rotor. A 3-D unsteady vortex-panel method potential flow solver based on a free-vortex-wake methodology is used for this purpose.

The solver is validated using the experimental data from the Caradonna-Tung experiments. The interactional analyses are performed for 10 different positions of the rear rotor with respect to the front rotor. The wake of the front rotor, which is generated due to the mutual interactions of the wake and tip vortices, is significantly asymmetric and non-uniform. Therefore, the rear rotor operates within a complex and vortical free-stream flow. The interaction of the incoming wake flow and the rear rotor generates a large, asymmetric wake region downstream of the rear rotor. The wake-rotor interactions cause substantial variations in the forces generated by the rear rotor. These variations also depend on the lateral variations of the rear rotor with respect to the front one.

Yen, K. T.

"THE AERODYNAMICS OF A JET IN A CROSSFLOW"

NADC-78291-6, December 1978, Naval Air Development Center, Warminster, PA

The aerodynamics of a jet in a crossflow considered as the key problem in transition aerodynamics for VSTOL aircraft has been reviewed. Experimental results on the flow structure of the jet, the contrarotating vortices, the jet entrainment phenomenon, and the surface pressure distributions have been analyzed. The influences on these characteristics by the jet parameters such as the velocity ratio, injection angle and jet orifice shape have been considered based on available measurements. In the theoretical area, particular attention has been directed to the methods of prediction and analysis, and the fundamental physical bases of these methods. Current developments in transition aerodynamics, and some recent work on the formation of contrarotating vortices and the wake flow are described.

Yen, S. C. and Hsu, C. M.

"INVESTIGATION ON VORTEX SHEDDING OF A SWEEP-BACK WING"

Experimental Thermal and Fluid Science, Vol. 31, 2007, pp. 849-855.

Effects of Reynolds number and angle of attack on the vortex shedding of a finite swept-back wing are experimentally studied. The cross-sectional profile of the wing is NACA 0012, and the sweep-back angle is 15 degrees. The time series signals detected by hot-wire in the wake region shows four distinct behaviors: laminar, subcritical, transitional, and supercritical. The derived Strouhal number curves are significantly different in these four behaviors. In addition, the statistical properties of turbulence, that is, the power spectrum density function, probability density function, correlation coefficient, Lagrangian integral time scales, and length scales are also presented in this paper.

Yeshala, N., Egolf, T. A., Vasilescu, R. and Sankar, L. N.

"APPLICATION OF HIGHER ORDER SPATIALLY ACCURATE SCHEMES TO ROTORS IN HOVER"

AIAA Paper No. 2006-2818, San Francisco, CA, June 2006.

The accuracy of the calculation of the tip vortex magnitude and the trajectory is very important in rotor calculations, especially in hover where it is the source of the induced velocity that in turn affects the aerodynamic loads. Lower order schemes do not give results of required accuracy due to the excessive diffusive error on practical grids. As a result, the use of spatially accurate schemes, with less diffusion error, is of prime importance in increasing the accuracy of the solution. In this study, two spatially high order schemes (Weighted Essentially Non-Oscillatory 7th (WENO7) and its 5th order counterpart (WENO5) are studied. Results are presented for performance characteristics and flow field structures. It is found that WENO7 scheme outperforms the 5th order scheme, provided an adequately refined grid with modest stretching factors is used.

Yeung, A. and Bramesfeld, G.

"MEASURING ATMOSPHERIC GUSTS AT LOW ALTITUDE"

AIAA Paper 2017-4076, June 2017, Denver, CO.

A small unmanned aerial vehicle was developed with the specific objective to explore atmospheric wind gusts at low altitudes of less than 200 m above ground. The small unmanned aerial vehicle is equipped with an air-data system that has been adapted for this specific application. The air-data system estimates the local wind gusts in the order 0.5 m/s by evaluating inputs from a five-hole probe, an inertial measurement unit, and a system that evaluates the differential carrier frequency phase shift of the GPS signal. The subsequently derived wind gust profiles will be used to improve gust models for the design and operation of small unmanned aerial vehicles. At this point, several successful test flights have been performed using the small unmanned aerial vehicle. Preliminary results of the wind profile and gusts encountered are presented in this paper.

Yeung, A. F. K. and Lee, B. H. K.

"PARTICLE IMAGE VELOCIMETRY STUDY OF WING-TIP VORTICES"

J. Aircraft, Vol. 36, No. 2, March-April 1999, pp. 482-484

Velocity measurements of wing-tip vortices have been obtained successfully in the Institute for Aerospace Research 9 m X 9 m wind tunnel using the Particle Image Velocimetry (PIV) technique. At 14-deg. angle of attack, the wing-tip vortices have been found to be highly unsteady, and the PIV technique has been shown to be an effective tool in obtaining instantaneous measurements of such unsteady flows. Further work is underway to refine its operation and extend its applicability under a wider range of flow conditions.

Yeung, A. F. K. and Lee, B. H. K.

"PIV STUDY OF WING TIP VORTICES IN THE IAR 9M X 9M WIND TUNNEL"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 91-93

The wing tip vortex of an unswept wing has been studied in the Institute for Aerospace Research (IAR) 9m by 9m wind tunnel using the particle image velocimetry (PIV) technique. The model used was a 14-inch chord, 5-foot (half-) span wing having a NACA0015 profile and mounted vertically on the floor of the test section. The angle of attack was set at 14 degrees. Protected by a Plexiglas casing and mounted on a tripod inside the test section, the PIV camera was placed approximately 6 chord lengths downstream of the measurement plane. The image covers a physical area of 320mm x 240mm, the largest measurement area with acceptable velocity measurements for the present flow configuration and seeding arrangements. The PIV system was used to measure the crossflow components of the wing tip vortex at approximately ten chord lengths downstream of the airfoil. The preliminary results presented in this paper were obtained at a wind speed of 15 mph (6.7 m/s) and a chord Reynolds number of 130,000. Vaporized bay oil, released in the settling chamber through a small nozzle, was used as the seeding material. For the present flow condition, the smoke nozzle was approximately 17 ft above the floor of the 82-ft diameter settling chamber.

Yi, H., Jinwen, Y. and Feng, B.

"WAKE VORTEX CONTROL USING MODIFIED FLAPS"

Applied Mechanics and Materials, Vols. 365-366, 2013, pp. 827-834.

The present paper is on the experimental investigation of a potentially effective method to alleviate the strength of aircraft wake vortex. The research work was carried out in a water-towing tank which equipped with a 2-D PIV system. By using modified flaps attached to the baseline-airfoil, the Rayleigh-Ludwig instability of the wake vortex was activated, resulting in a premature dissipation of the wake vortex. The experimental results of PIV measurement exhibited that the circulation of the wake vortex was reduced to over 50 percent for the optimal case at 45 wingspans downstream with suitable settings, which proved the effectiveness of the modified-flap treatment in alleviating the wake vortex under labor conditions.

Yi, H., Jinwen, Y. and Feng, B.

"THE INSTABILITY OF A FOUR-VORTEX WAKE SYSTEM IN A WATER TOWING TANK"

Advanced Materials Research, Vols. 756-759, 2013, pp. 1484-1488.

A simplified rectangular baseline-airfoil model attached with tailored flaps was designed to study the Rayleigh-Ludwig instability by tailoring a four-vortex wake system. By means of PIV measurement in a water towing tank, the interaction process and circulation evolution of the wake system were obtained systematically. The circulation remains was reduced to ca. 40 percent after 43 wingspans which proved the application potentials of this method in alleviating the wake vortex.

Yildirim, E. and Hillier, R.

"NUMERICAL MODELING OF THE IMPULSIVE ORTHOGONAL CUTTING OF A TRAILING VORTEX"

Shock Waves, Vol. 23, 2013, pp. 369-379.

This paper presents inviscid compressible simulations for the impulsive blocking of a vortex, with nonzero axial velocity along its core, by a flat plate orthogonal to the vortex axis. This is a simplified model of the blade-vortex interaction between the tail rotor of a helicopter and the trailing vortex system formed by the main rotor system. There are two important elements to this phenomenon. One is the vortex response, including a physical description for the evolution of complex vortical structures near the plate surface, and the second is the resultant pressure wave structure and the manner of its propagation away from the plate surface. This paper focuses more on the vortex structure, and how this is affected by compressibility and the initial transient shock structures that form at the plate surface.

Yoshifumi, K., Zawadzki, I. and Aref, H.

"VORTEX MOTION, SOUND RADIATION, AND COMPLEX TIME SINGULARITIES"

Phys. Fluids, Vol. A 2, No. 2, February 1990, pp. 214-21.

The equation of motion for interacting point vortices can be embedded in a system of ordinary differential equations with polynomial couplings and thus subjected to the 'Painleve test' for integrability. The arrays of singularities produced by this analysis confirm well known results on integrability and chaos in few-vortex systems, and are shown by further numerical experiments to predict qualitative features of the low Mach number sound radiation from the vortex system. The correspondence between singularity distribution, vortex trajectory pattern, time series of far-field pressure, and sound spectrum are illustrated and discussed based on a parametric numerical survey of some simple three- and four-vortex motions. The results suggest a physical interpretation of the Painleve singularities.

Yoshikawa, E. and Matayoshi, N.

"WAKE VORTEX OBSERVATION CAMPAIGN BY ULTRA FAST-SCANNING LIDAR IN NARITA AIRPORT, JAPAN"

ICAS 2014, September 2014, St. Petersburg, Russia.

The Japan Aerospace Exploration Agency (JAXA) is conducting a wake vortex observation campaign at Narita airport, Japan to evaluate the probabilistic properties of wake vortex behaviors. Based on the probabilistic properties derived from many observation data, the current safe wake vortex separation minima can be revised and airport capacity is increased without any loss of safety. In our observation campaign, an ultra-fast scanning lidar is used to obtain a large number of wake vortex behaviors with high accuracy and temporal resolution. This paper presents an overview of our observation campaign, collected data, and initial analyses.

Yoshikawa, E. and Matayoshi, N.

"AIRCRAFT WAKE VORTEX RETRIEVAL METHOD ON LIDAR LATERAL RANGE-HEIGHT INDICATOR OBSERVATION"

AIAA Journal, Vol. 55, No. 7, July 2017, pp. 2269-2278.

An aircraft wake vortex retrieval method that estimates the horizontal and vertical positions and radii-averaged circulations of wake vortices from lidar-measured Doppler spectra on a lateral range-height indicator is proposed. The method formulates relationships between state variables and measured Doppler spectra for each individual wake vortex and iteratively optimizes the state variables so as to match the measured Doppler spectra. Because the state variables consist of a position, the parameters of an assumed two-dimensional vortex model, and a local background wind, high retrieval accuracy is achieved without adverse influences from errors in the pre-estimation of position or background wind. The separate formulation of each wake vortex enables the method to flexibly handle nonideal cases, for example where only one wake vortex of a pair remains or a long-persistent wake vortex and a newly generated pair of wake vortices coexist on a single range-height indicator. The retrieval results were evaluated against reference flight data from 864 flights collected during a wake vortex observation campaign conducted by the Japan Aerospace Exploration Agency at Narita International airport. The evaluation was performed by an approach using self- and cross-evaluation models, which allowed the evaluation of many retrievals considering time variation of the wake vortex parameters. As a result, the proposed method was found to retrieve horizontal position with a bias error of 0.2 m and a standard error of 4.8 m; vertical position with bias and standard errors of -1.7 and 3.5 m, respectively; and radii-averaged circulation with bias and standard errors of +31.5 and 32.3 square m per s, respectively.

Yoshikawa, E. and Matayoshi, N.

"DETECTION AND ESTIMATION OF WAKE VORTEX ON ULTRA FAST-SCANNING PULSED-DOPPLER LIDAR"

ICAS 2004, Paper 2004-0186, September 2014, St. Petersburg, Russia.

An algorithm for the detection and estimation of a wake vortex using a lateral Range Height Indicator (RHI) observation of a pulsed-Doppler lidar is proposed. By estimating physical parameters from measured Doppler spectra, the proposed method achieves high accuracy and robustness even in low Carrier-to-Noise Ratio (CNR) conditions. This paper describes the methodology and presents an initial evaluation with data collected in a wake vortex observation campaign at Narita Airport, Japan.

Yoshitake, S., Hayashi, H., Sasaki, S. and Fukano, T.

"RELATIONSHIP BETWEEN AEOLIAN TONE AND WAKE VORTEX FROM INCLINED FLAT BLADE"

Journal of Fluid Science and Technology, Vol. 4, No. 3, 2009, pp. 775-785.

The three-dimensional structure of the wake vortex was investigated in relating to the aeolian tone from the inclined blade. It was pointed out that the aeolian tone is largest not at zero, but at ten degrees of the inclined angle. The correlation length of the wake vortex in span becomes large at small inclined angles. The large-scale structures of the wake vortex are generated in zero and ten degrees of inclined angle. The shape of the structure is influenced with the span-wise velocity in the dead air region. There are small scale spots of the pressure fluctuation at the trailing edge. The spots are interacted each other and make a large cluster of the pressure fluctuation. It is proposed that the scale of it is decided by the timing of the wake vortex formation. And the shape of the wake vortex structure is closely related with the scale of it. The correlation length of the wake vortex is calculated from the shape of the structure. The estimation of aeolian tone by using the length with Fukano's model is well coincided to experiments.

You, Y. H., Sa, J. H., Park, J. S., Park, S. H. and Jung, S. N.

"MODERN COMPUTATIONAL FLUID DYNAMICS/STRUCTURAL DYNAMICS SIMULATION FOR A HELICOPTER IN DESCENT"

Journal of Aircraft, Vol. 50, No. 5, September-October 2013, pp. 1450-1464.

In this work, several computational-fluid-dynamics-based approaches are employed to validate the airloads, trim angles, blade elastic motions, vortex positions, and structural loads of a rotor in low-speed, descending flight. To this end, two different comprehensive codes, CAMRAD II and DYMORE, are coupled with a computational fluid dynamics code, KFLOW, using a loose coupling methodology. A computational fluid dynamics approach using the measured blade motions is also carried out for the validation. For both clarity and consistency required in the relative comparison between different methods, an identical computational fluid dynamics grid system is used for the study. A fuselage effect is considered in the analysis. The predicted results are correlated against the measured data. CAMRAD II coupling shows good prediction for low-frequency loadings, elastic motions, and structural lag bending and torsion moments. DYMORE coupling demonstrates good matches on trim control angles, blade vortex interaction airloads, and structural flap bending but less satisfactory for lag motions. Initial results indicate poor correlation on aeropitching moments. This discrepancy is seen to be fixed when considering the actual pressure sensor locations used in the test. The blade-vortex miss distance at a desired instant is also evaluated. About 25 percent larger miss distance is obtained with a higher harmonic control input.

Young, L. A.

"ROTOR VORTEX FILAMENTS: LIVING ON THE SLIPSTREAM'S EDGE"

NASA TM- 110431, January 1997, Ames Research Center, Moffett Field, CA

The purpose of this paper is to gain a better understanding of rotor wake evolution in hover and axial flow by deriving an analytical solution for the time dependent behavior of vortex filament circulation and core size. This solution is applicable only for vortex filaments in the rotor far-wake. A primarily

inviscid vortex/shear layer interaction (where the slipstream boundary is modeled as a shear layer) has been identified in this analytical treatment. This vortex/shear layer interaction results in decreasing vortex filament circulation and core size with time. The inviscid vortex/shear layer interaction is shown, in a first-order treatment, to be of greater magnitude than viscous diffusion effects. The rate of contraction, and ultimate collapse, of the vortex filament core is found to be directly proportional to the rotor inflow velocity. This new insight into vortex filament decay promises to help reconcile several disparate observations made in the literature and will, hopefully, promote new advances in theoretical modeling of rotor wakes.

Young, L. A.

"A FAMILY OF VORTICES TO STUDY AXISYMMETRIC VORTEX BREAKDOWN AND RECONNECTION"

AIAA Paper No. 2007-4447, Miami, FL, June 2007

A new analytic model describing a family of vortices has been developed to study some of the axisymmetric vortex breakdown and reconnection fluid dynamic processes underlying body-vortex interactions that are frequently manifested in rotorcraft and propeller-driven fixed-wing aircraft wakes. The family of vortices incorporates a wide range of prescribed initial vorticity distributions -- including single or dual-core vorticity distributions. The result is analytical solutions for the vorticity and velocities for each member of the family of vortices. This model is of sufficient generality to further illustrate the dependence of vortex reconnection and breakdown on initial vorticity distribution as was suggested by earlier analytical work. This family of vortices, though laminar in nature, is anticipated to provide valuable insight into the vortical evolution of large-scale rotor and propeller wakes.

Young, L. A.

"INFLUENCE OF INITIAL VORTICITY DISTRIBUTION ON AXISYMMETRIC VORTEX BREAKDOWN AND RECONNECTION"

AIAA Paper No. 2007-1283, Reno, NV, January 2007

An analytical treatment has been developed to study some of the axisymmetric vortex breakdown and reconnection fluid dynamic processes underlying body-vortex interactions that are frequently manifested in rotorcraft and propeller-driven fixed-wing aircraft wakes. In particular, the presence of negative vorticity in the inner core of a vortex filament (one example of which is examined in this paper) subsequent to 'cutting' by a solid body has a profound influence on the vortex reconnection, leading to analog flow behavior like vortex breakdown phenomena described in the literature. Initial vorticity distributions (three specific examples which are examined) without an inner core of negative vorticity do not exhibit vortex breakdown and instead manifest diffusion-like properties while undergoing vortex reconnection. Though this work focuses on laminar vortical flow, this work is anticipated to provide valuable insight into rotary-wing aerodynamics as well as other types of vortical flow phenomena.

Young, L. A.

"VORTEX CORE SIZE IN THE ROTOR NEAR-WAKE"

NASA/TM-2003-212275, June 2003, NASA Ames Research Center, Moffett Field, CA

Using a kinetic energy conservation approach, several simple analytic expressions are derived for estimating the core size of tip vortices in the near-wake of rotors in hover and axial-flow flight. The influence of thrust, induced power losses, advance ratio, and vortex structure on rotor vortex core size is assessed. Experimental data from the literature is compared to the analytical results derived in this paper.

Young, L. A.

"MODELING OF A TURBULENT LINE VORTEX"

AIAA Paper 2008-3801, June 2008, Seattle, WA.

There is considerable interest in turbulence modeling of vortical structure. The most fundamental of all such structures is the line, or columnar, vortex. Many laminar flow solutions of line vortices have been reported in the literature. Only a few analytical treatments have been presented for turbulent line vortex modeling. More contemporary predictive work has focused on performing highly refined higher-order CFD predictions of vortices for specific areas of interest -- in particular, examining wing/blade-tip trailed vortex roll-up or far-field wake temporal evolution. In almost all cases, the turbulence closure models are not necessarily well suited for the high gradients and rotational effects typical of wing/rotor trailed tip vortices. Recently, though, there have been several computational studies of turbulent vortices that have adopted highly sophisticated direct numerical simulations of the unsteady Navier-Stokes momentum equations. This work has been very promising in terms of understanding not only the mean flow behavior of turbulent vortices but their higher-order characteristics as well. Nonetheless, there remains much still to learn about turbulent vortices in general. In particular, the transition flow mechanism from laminar to fully turbulent vortex states is still largely undetermined. A new analytical approach is suggested in this paper. The result is progress towards a turbulent line vortex model that captures many of the flow features previously observed, predicted, and/or conjectured about this fundamental building block of the vortical fluid flow, including, most importantly, the transition from laminar to turbulent flow states.

Young, L. A.

"VORTEX FILAMENT EVOLUTION SUBJECT TO PULSED/PERIODIC DISRUPTION"

AIAA Paper No. 2008-367, Reno, NV, January 2008

There is considerable interest within the fixed- and rotary-wing research communities as to discovering how fixed- and rotary-wing trailed tip vortices might be modified or controlled. The reasons for attempting such vortical flow control are many but success to date has been very modest. This is primarily the case because the vortical flow physics are still not adequately understood. A new

analytic model describing the flow behavior resulting from pulsed or periodic disruption to line vortices is described. Such vortex filament disruption is manifested in three different forms: spatial cuts or breaks, embedded inner core negative vorticity, and/or sinusoidal varying circulation. These are three possible strategies by which vortex filament strength and geometry can perhaps be modified through passive or active control mechanisms. Finally, an additional analysis is presented that examines the feasibility of destabilizing vortical structures, thereby representing a fourth potential approach for active flow control. The presented work describes a wide array of unsteady flow phenomena that are highly pertinent to the question of active control of trailed rotary- and fixed-wing vortices.

Young, L. A., Yamauchi, G. K. and Rajagopalan, G.

"SIMULATED ROTOR WAKE INTERACTIONS RESULTING FROM CIVIL TILTROTOR AIRCRAFT OPERATIONS NEAR VERTIPORT TERMINALS"

AIAA Paper 2013-0801, January 2013, Grapevine, TX.

A mid-fidelity computational fluid dynamics tool called RotCFD -- specifically developed to aid in rotorcraft conceptual design efforts -- has been applied to the study of rotor wake interactions of civil tiltrotor aircraft in the immediate vicinity of vertiport/airport ground infrastructure. This issue has grown in importance as previous NASA studies have suggested that civil tiltrotor aircraft can potentially have a significant impact on commercial transport aviation. Current NASA reference designs for such civil tiltrotor aircraft are focused on a size category of 90-120 passengers. Notional concepts of operations include simultaneous non-interfering flight into and out of congested airports having vertiports, that is, prepared VTOL takeoff and landing zones, or underutilized short runways for STOL operation. Such large gross-weight vehicles will be generating very high induced velocities. Inevitably, the interaction of the rotor wake with ground infrastructure such as terminal buildings and jetways must be considered both from an operational as well as design perspective.

Youssef, K. S.

"NUMERICAL INVESTIGATION OF THE WAKE OF A RECTANGULAR WING"

PhD Thesis, March 1998, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Wakes of lifting bodies contain vortex sheets that roll up into strong streamwise vortices. The long-time behavior of such vortices depends on the turbulence in the wake and the stability characteristics of the vortices themselves. In the near wake of a rectangular wing the flow field consists of a spiraling wake that winds around a pair of vortex cores. The study of the turbulence structure and life of wing tip vortices is of great importance to air traffic control in congested airports. In this dissertation a computer code is developed for the temporal as well as spatial simulations of trailing vortices. A sixth-order compact finite-difference method is used in the cross plane. The streamwise derivatives are represented either by a Fourier series for temporal simulations (periodic flow) or by a sixth-order compact scheme for spatial simulations. The time marching scheme is a third-order Runge-Kutta

method. The code is used to study the nonlinear development of temporal helical instability waves in a trailing vortex. Contours of a passive scalar are used to study the entrainment process that redistributes angular and axial momenta between the core and its surroundings. Such a process leads to quenching of the instability waves in the vortex core. The code is also used to predict the spatial development of mean flow in the wake of a rectangular wing. New treatment of the outflow boundary condition on the pressure is formulated so that a strong streamwise vortex can exit the computational domain without distortion. Temporal large-eddy simulation (LES) is performed to study the development of large-scale structure in the wake and their interaction with the tip vortex. A modified MacCormack scheme developed by Gottlieb and Turkel (1976) has been used to solve the LES equations. A model of the initial conditions in the near wake of a rectangular wing is devised to investigate mechanisms of turbulence production in the spiral wake around the core of a tip vortex. The model consists of a streamwise vortex sheet whose strength is found from Prandtl lifting line theory. A Gaussian streamwise velocity profile is superimposed on the field of the vortex sheet. This profile represents the spanwise vorticity. The integrated spanwise vorticity of this profile is zero. A novel feature of this study is that the mean flow contains both streamwise and spanwise vorticity. The model is then used to initialize the flow field for temporal LES of the instabilities of the spanwise vorticity during roll up. The results show that the sinuous mode prevails in the spiral wake around the core. The strength and streamwise length scale of the instability vary along the span because of the continuous variation of the wake thickness due to stretching by the tip vortex. The large-scale structures produced by the instability of the spiral wake cause the formation of undulations on the core -- consistent with the hypothesis of Davenport et al. (1996).

Youssef, K. S., Ragab, S. A., Devenport, W. J. and Gawad, A. F. A.

"LARGE EDDY SIMULATION OF THE NEAR WAKE OF A RECTANGULAR WING"

AIAA Paper No. 1998-0317, Reno, NV, January 1998

A model of the initial conditions in the near wake of a rectangular wing is devised to investigate mechanisms of turbulence production in the spiral wake around the core of a tip vortex. The model consists of a streamwise vortex sheet whose strength is found from Prandtl lifting line theory. Spanwise vorticity is represented by a Gaussian streamwise velocity profile that is superimposed on the field of the vortex sheet. The integrated spanwise vorticity of this profile is zero. The model is then used to initialize the flow field for temporal large-eddy simulation of the instabilities of the spanwise vorticity during roll up. The results show that the sinuous mode prevails in the spiral wake around the core. The strength and streamwise length scale of the instability vary along the wake because of the continuous variation in its thickness. The large-scale structures produced by the instability of the spiral wake cause the formation of undulations on the core.

Yu, Y.-S., Du, X.-D. and Wei, Q.-D.

"VISUALIZATION AND MEASUREMENT FOR WINGTIP VORTEX"

Proceedings of 6th Triennial Int'l. Symposium on Fluid Control, Measurement and Visualization, Flucome 2000, August 2000, Sherbrooke, Canada.

The structure of wingtip vortex and the affections of taps on wingtip vortex are studied experimentally. Four different kinds of taps are mounted on the tip of a wing respectively during the experiment. The vortex structure and the damping process of the wingtip vortex are visualized by use of hydrogen bubbles in a towing tank. The azimuthal velocity within the cross sections which correspond to different downstream positions are measured through LDV in a water tunnel. The results from the visualization and measurements indicate that the taps will obviously affect the structure of the wingtip vortex at initial stage but not when the vortex goes downstream. The taps have little affection on the damping process of wingtip vortex.

Yu, Z., Chapelier, J.-B. and Scalo, C.

"COHERENT-VORTICITY PRESERVING LARGE-EDDY SIMULATION OF VORTEX RINGS UNDER LARGE PERTURBATIONS"

AIAA Paper 2018-4035, June 2018, Atlanta, GA.

In this paper, a numerical study of the dynamics of a perturbed vortex ring is conducted using Coherent-vorticity Preserving (CvP) Large-Eddy simulation spanning circulation-based Reynolds numbers in the range 7,000-700,000. The vortex line corresponding to the vortex ring is defined using a parametric equation and perturbed with amplitude in the range of 10-20 percent of the radius. Two types of perturbations are tested: sinusoidal (mode 10) and multi-mode. The Biot-Savart law is employed to define the corresponding induced velocity field. High levels of perturbation yield a transient bursting stage of the original vortex ring and the formation of a new one. The generation of dipoles and different types of vortex reconnection are accurately captured by the CvP-LES. Vortex bursting is observed with large amplitude perturbations at the beginning of simulations. The ejection of dipoles at the inner and outer sides extracts vorticity from the vortex ring which loses its coherence immediately. Dipoles keep growing and the vortex core intensifies in the form of tangled vortex threads up to breakdown, leaving stable dipoles. Dipoles go through a viscous cancellation process and the vortex core is then slightly restored. The reasons of the persistence of coherent structures in all types of perturbations are analyzed. An axial flow, i.e. a flow along the vortex line is detected with multi-mode perturbation simulations, which is driven by the pressure gradient resulting from ejected dipoles and develops from nonuniform locations of pressure sources.

Yu, Z., Qu, Y. and Zhang, Y.

"SAFE CONTROL OF TRAILING UAV IN CLOSE FORMATION FLIGHT AGAINST ACTUATOR FAULT AND WAKE VORTEX EFFECT"

Aerospace Science and Technology, Vol. 77, 2018, pp. 189-205.

In the close formation flight, the wake vortex induced by the leading aircraft will have adverse effects on the safe flight of the trailing unmanned aerial vehicle (UAV). Hence, this paper investigates a

difficult problem of safe control for the trailing UAV against actuator faults, input saturation, and wake vortex effect. By using disturbance observers, external wake vortex, disturbances, and internal actuator faults are estimated. Then, with the help of estimated knowledge of disturbance, backstepping control laws are developed for the longitudinal dynamics and the lateral-directional dynamics, respectively. One of the key features of the proposed strategy is that, the inherent problem, i.e., 'explosion of complexity' in conventional backstepping control, is solved by the presented dynamic surface control scheme. Another key feature is that external wake vortex, disturbances, and internal actuator faults, input saturation are simultaneously considered. It is shown by Lyapunov stability analysis that the closed-loop system is uniformly ultimately bounded with safety requirements guaranteed even in the presence of wake vortex and actuator faults. The effectiveness of the proposed approach is further validated by simulation results.

Yuan, S. W.

"VORTEX CONTROL"

US Patent 3,936,013, February 1976.

This invention is for wings of all types, such as fixed wings for aircraft and hydrofoil boats, and rotary blades (or wings) for helicopters and turbines, to be equipped with a slotted tube, or a tube with series of holes extending outwardly in the spanwise direction near the trailing edge of the wing tip for blowing jets of fluid (such as air or water) in the direction opposite to the lift of the wing, thereby achieving flow in the form of a jet sheet to abate, diffuse and break up the undesirable wing-tip or blade-tip vortices.

Yuan, S. W.

"VORTEX POLLUTION-WING-TIP VORTICES: THE HAZARD AND THE REMEDY"

Aeronautical Soc. of India Journal, Vol. 23, May 1971, pp. 67-70

A device has been developed for controlling wing tip vortices, and its effectiveness has been verified by wind-tunnel testing. Multiple apertures (or a continuous slot) extending along the chordwise direction of the wing tip are used for blowing tangential jets of gas at preselected locations. Rows of vortices are thus produced to counterbalance the undesirable wing-tip vortices. The small amount of gas required can be bled off from the jet engine through a conduit, or it can be generated locally. The system improves lift efficiency and increases the volume of airport landing and takeoff operations by shortening the separation requirements dictated by vortex hazards.

Yuan, S. W.

"WING-TIP VORTICES CONTROL"

US Patent 3,692,259, September 1972.

This invention is for wings of all types, such as fixed wings for aircraft and hydrofoil boats, and rotary blades (or wings) for helicopters and turbines, to be equipped with a row of chordwise tangential jets along the edge or end surfaces of the wing tips for counter-balancing and controlling the wing-tip or blade-tip vortices.

Yuan, S. W. and Bloom, A. M.

"EXPERIMENTAL INVESTIGATION OF WING-TIP VORTEX ABATEMENT"

International Council of the Aeronautical Sciences, Paper 74-35, Haifa, Israel, 1974.

Detailed measurements of aerodynamic forces and downstream velocity distributions of a model airplane with and without vortex abatement device have been made. Time-mean-average velocity components were measured, using an triple-sensor hot film probe, at 1/2-chord and 5-chord distances behind the trailing edge of the wing. The results of these tests clearly indicate that not only does the vortex abatement device reduce greatly the size of the wing-tip vortex but also the strength of the vortex core. The effect of the vortex abatement device also results in a considerable increase in lift and decrease in drag.

Yue, L., Junwei, W., Zhirong, L. and Feng, B.

"EXPERIMENTAL INVESTIGATION OF WAKE VORTEX IN A WATER-TOWING-TANK"

Proceedings SPIE, Vol. 8417, 6th International Symposium on Advanced Optical Manufacturing and Testing Technologies, October 2012, pp. 84172Y-1 - 84172Y-8.

Wake vortex behind an aircraft would introduce great hazard to the following aircraft and threat to the flight safety. Generic model using two rectangular airfoils was employed for generating wake vortex system to investigate the method of wake vortex alleviation. The investigation was carried out in a water towing tank equipped with Particle Image Velocimetry system. Characteristics of double-vortex flow were analyzed for selected cases, proving that the intensity of the vortex is reduced with respect to the interaction between the wake vortices. The study exhibited that the R-L instability was most effectively triggered with parameter combinations of angles of attack 10 and 8 degrees and $b = 50\text{mm}$ respectively. As a result, the circulation of the wake vortices was alleviated by nearly 40 percent accordingly.

Yuen, H. C.

"WAVES ON VORTEX FILAMENTS"

Ph.D. Thesis, May 1973, California Institute of Technology, Pasadena, CA

Various problems concerning waves on vortex filaments are considered. The local force balance method introduced by Moore and Saffman for the calculation of the induced velocity at a point of a

vortex filament with arbitrary structure and shape is used to examine the effect of axial flow on the stability of trailing vortices and vortex rings. It is found that the effect is small in both cases.

Zaitsev, M. Y., Kop'ev, V. F. and Kotova, A. N.

"REPRESENTATION OF THE SOUND FIELD OF A TURBULENT VORTEX RING AS A SUPERPOSITION OF QUADRUPOLES"

Acoustical Physics, Vol. 47, No. 6, 2001, pp. 699-706

Results of an experimental study of the directivity of noise produced by a turbulent vortex ring ($Re = 100,000$) are presented. The acoustic measurements were performed in an anechoic chamber by a circular array of microphones with its center lying at the symmetry axis of the ring. A method of a synchronous processing of acoustic signals is proposed. This method allows one to separate different quadrupole components in the measured sound field of a turbulent vortex.

Zak, J. A.

"ATMOSPHERIC BOUNDARY LAYER SENSORS FOR APPLICATION IN A WAKE VORTEX ADVISORY SYSTEM"

NASA/CR-2003-212175, April 2003, Vigyan, Inc., Hampton, VA.

Remote sensing of the atmospheric boundary layer has advanced in recent years with the development of commercial off-the-shelf (COTS) radar, sodar, and lidar wind profiling technology. Radio acoustic sounding systems for vertical temperature profiles of high temporal scales (when compared to routine balloon soundings (radiosondes)) have also become increasingly available as COTS capabilities. Aircraft observations during landing and departures are another source of available boundary layer data. This report provides an updated assessment of available sensors, their performance specifications and rough order of magnitude costs for a potential future aircraft Wake Vortex Avoidance System (WakeVAS). Future capabilities are also discussed. Vertical profiles of wind, temperature, and turbulence are anticipated to be needed at airports in any dynamic wake avoidance system. Temporal and spatial resolution are dependent on the selection of approach and departure corridors to be protected. Recommendations are made for potential configurations of near-term sensor technologies and for testing some of the sensor systems to validate performance in field environments with adequate ground-truth.

Zak, J. A. and Rodgers, Jr., W. G.

"ATMOSPHERIC BOUNDARY LAYER WIND DATA DURING THE PERIOD JANUARY 1, 1998 THROUGH JANUARY 31, 1999 AT THE DALLAS-FORT WORTH AIRPORT. VOLUME 2 - DATA AND PROCESSING"

NASA/CR-2000-210323 Vol. 2, August 2000, Vigyan, Inc., Hampton, VA.

The NASA Langley Research Center's Aircraft Vortex Spacing System (AVOSS) requires accurate winds and turbulence to determine aircraft wake vortex behavior near the ground. Volume 1 described the wind input and quality analysis process. This volume documents the data available during the period January 1998 through January 1999 and the partitioning and concatenation of files for time of day, turbulence, non-duplication, cross wind profile quality and ceiling and visibility. It provides the resultant filtered files for the first three partitions as well as identification of ceiling/visibility conditions when they were below 5000 feet and 5 miles respectively. It also includes the wind profile quality flags to permit automatic selection of files for AVOSS application using selected ceiling/visibility and wind profile quality values and flags (or no flags).

Zak, J. A. and Rodgers, Jr., W. G.

"PREPROCESSING FOR EDDY DISSIPATION RATE AND TKE PROFILE GENERATION"

NASA CR-2001-210834, March 2001, NASA Langley Research Center, Hampton, VA

The Aircraft Vortex Spacing System (AVOSS), a set of algorithms to determine aircraft spacing according to wake vortex behavior prediction, requires turbulence profiles to appropriately determine arrival and departure aircraft spacing. The ambient atmospheric turbulence profile must always be produced, even if the result is an arbitrary (canned) profile. The original turbulence profile code was generated by North Carolina State University and used in a non-real time environment in the past. All the input parameters could be carefully selected and screened prior to input. Since this code must run in real-time using actual measurements in the field as input, it became imperative to begin a data checking and screening process as part of the real-time implementation. The process described herein is a step towards ensuring that the best possible turbulence profile is always provided to AVOSS. Data fill-ins, constant profiles and arbitrary profiles are used only as a last resort, but are essential to ensure uninterrupted application of AVOSS.

Zak, J. A. and Rodgers, Jr., W. G.

"OBSERVED CHANGES IN ATMOSPHERIC BOUNDARY LAYER PROPERTIES AT MEMPHIS INTERNATIONAL AIRPORT DURING AUGUST 1995"

NASA CR-4786, September 1997, pp. 68

As part of the NASA Terminal Area Productivity Program, Langley Research Center embarked on a series of field measurements of wake vortex characteristics and associated atmospheric boundary layer properties. One measurement period was at the Memphis International Airport in August 1995. Atmospheric temperature, humidity, winds, turbulence, radiation, and soil properties were measured from a variety of sensor systems and platforms including sodars, profilers, aircraft, and towers. This

research focused on (1) changes that occurred in tower data during sunrise and sunset transitions, (2) vertical variation of temperature and cross-head winds at selected times utilizing combinations of sensors, and (3) changes measured by an OV-10 aircraft during approaches and level flights. Significant but not unusual changes are documented and discussed in terms of expected boundary layer behavior. Questions on measurement and prediction of these changes from existing and near-term capabilities are discussed in the context of a future Aircraft Vortex Spacing System.

Zak, J. A. and Rodgers, Jr., W. G.

"DOCUMENTATION OF ATMOSPHERIC CONDITIONS DURING OBSERVED RISING AIRCRAFT WAKES"

NASA CR-4767, April 1997, ViGYAN, Inc., Hampton, VA

Flight tests were conducted in the fall of 1995 off the coast of Wallops Island, Virginia, to determine characteristics of wake vortices at flight altitudes. A NASA C-130 aircraft equipped with smoke generators produced visible wakes at altitudes ranging from 775 to 2225 m in a variety of atmospheric conditions, orientations (head wind, cross wind), and airspeeds. Meteorological and aircraft parameters were collected continuously from an OV-10A aircraft as it flew alongside and through the wake vortices at varying distances behind the C-130. Vortices were observed to rise at distances beyond a mile behind the C-130. The maximum altitude was 150 m above the C-130 in a near neutral atmosphere with significant turbulence. There were several cases when the vortices did not descend after a short initial period and remained near generation altitude in a variety of moderately stable atmospheres and wind shears.

Zak, J. A. and Rodgers, Jr., W. G.

"ATMOSPHERIC BOUNDARY LAYER WIND DATA DURING THE PERIOD JANUARY 1, 1998 THROUGH JANUARY 31, 1999 AT THE DALLAS-FORT WORTH AIRPORT - VOLUME 1 - QUALITY ASSESSMENT"

NASA/CR-2000-210323, Vol. 1, August 2000, Vigyan, Inc., Hampton, V.

The quality of the Aircraft Vortex Spacing System (AVOSS) is critically dependent on representative wind profiles in the atmospheric boundary layer. These winds observed from several sensor systems around the Dallas-Fort Worth airport were combined into single vertical wind profiles by an algorithm developed and implemented by MIT Lincoln Laboratory. This process, called the AVOSS Winds Analysis System (AWAS), is used by AVOSS for wake corridor predictions. During times when AWAS solutions were available, the quality of the resultant wind profiles and variance was judged from a series of plots combining all sensor observations and AWAS profiles during the period 1200 to 0400 UTC daily. First, input data was evaluated for continuity and consistency from criteria established. Next, the degree of agreement among all wind sensor systems was noted and cases of disagreement identified. Finally, the resultant AWAS solution was compared to the quality-assessed input data. When profiles differed by a specific amount from valid sensor consensus winds, times and altitudes were flagged. Volume one documents the process and quality of input sensor data. Volume two documents the data processing/sorting process and provides the resultant flagged files.

Zak, J. A., Rodgers, Jr., W. G. and Nolf, S.

"OPERATIONAL PERFORMANCE OF SENSOR SYSTEMS USED TO DETERMINE ATMOSPHERIC BOUNDARY LAYER PROPERTIES AS PART OF THE NASA AIRCRAFT VORTEX SPACING SYSTEM PROJECT"

NASA CR-2001-210835, March 2001, NASA Langley Research Center, Hampton, VA.

There has been a renewed interest in the application of remote sensor technology to operational aviation and airport-related activities such as AVOSS. Radio Acoustic Sounding Systems (RASS), Doppler-acoustic sodars, UHF profilers and lidars have many advantages in measuring wind and temperature profiles in the lower atmospheric boundary layer since they can operate continuously and unattended; however, there are limitations in their operational use at airports. For example, profilers deteriorate (limited altitude coverage or missing) in moderate or greater rain and can be affected by airplane targets in their field of view. Sodars can handle precipitation better but are affected by the high noise environments of airports and strong winds. Morning temperature inversions typically limit performance of RASS, sodars and profilers. Fog affects sonic anemometers. Lidars can have difficulties in clouds, fog or heavy precipitation. Despite their limitations these sensors have proven useful to provide wind and temperature profiles for AVOSS. Capabilities and limitations of these and other sensors used in the AVOSS program are discussed, parameter settings for the sensor systems are documented, and recommendations are made for the most cost-effective group of sensors for the future. The potential use of specially tuned dynamic forecast models and measurements from landing and departing aircraft are addressed.

Zak, J. A., Rodgers, W. G. and Rivers, R. A.

"OBSERVED AIRCRAFT RISING WAKES AT FLIGHT ALTITUDES"

Proceedings of the 8th Conference on Aviation, Range, and Aerospace Meteorology, Dallas, TX, January 1999

Flight tests were conducted in the fall of 1995 off the coast of Wallops Island, Virginia, to measure characteristics of wake vortices at flight altitudes. A NASA Wallops Flight Facility C-130 aircraft equipped with smoke generators produced visible wakes at altitudes ranging from 775 to 2225 m in a variety of atmospheric conditions, orientations (head wind, cross wind), and airspeeds. Meteorological data and aircraft parameters were collected from a Langley Research Center OV-10A aircraft as it flew alongside and through the wake vortices at varying distances behind the C-130. Meteorological data were also obtained from special balloon observations at Wallops Island. Differential GPS was used on each aircraft to obtain altitude profiles. Vortices were observed to rise at distances as close as 500 m behind the C-130. The wake was observed to be 150 m higher than the C-130 on one occasion at a distance of 11 km behind. The rising motion on this day was due to large vertical oscillations in the wakes. The atmospheric conditions were near neutral stratification with significant turbulence. There were several cases when the vortices did not descend after the first few minutes, and they remained near generation altitude in a variety of moderately stable atmospheres and wind shears. The FAA Wake Turbulence Training Aid is currently under revision to incorporate some of the data from this research.

Zakharov, S. B.

"A NOTE ON VORTEX MERGING"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 78-83

Inviscid merging of two, initially circular regions of a constant vorticity distribution have been investigated numerically and analytically using integral invariants of vorticity distribution in two-dimensional ideal fluid flow. Main factors affecting the merging process have been identified. Bifurcation diagram is shown in the plane of governing parameters. Generation of a resulting circular vortex with the area equal to the sum of the original vortices area has been proven.

Zakharov, V. E.

"QUASI-TWO-DIMENSIONAL HYDRODYNAMICS AND INTERACTION OF VORTEX TUBES"

Lecture Notes in Physics, Vol. 536, 1999, pp. 369-385

One motivation relates to the classical problem of the 'blow-up' in the Euler equation. According to the most plausible scenario, in the point of blow-up the vorticity becomes infinite. As far as vorticity is a vector, this assumption presumes that the flow near the blow-up point is almost two-dimensional and the velocity field is concentrated mostly in the plane orthogonal to the vorticity vector. An elaboration of this regular tool for description of this type of flow looks very timely. Another motivation is the vortex dynamics. This is a subject which has a chance to become the backbone of the future theory of turbulence. Probably, there is no way to explain qualitatively and quantitatively the fundamental phenomenon of intermittency but a careful study of the dynamics of the vortex tubes or their systems in a real three-dimensional nonstationary flow.

Zalay, A. D.

"HOT-WIRE AND VORTICITY METER WAKE VORTEX SURVEYS"

AIAA Journal, Vol. 14, May 1976, pp. 694-696

The vorticity meter used in the experiments consists of a paddle-wheel sensor mounted on a rotating shaft and fitted with a jeweled bearing. Vorticity data for a trailing vortex obtained with the vorticity meter are presented in a graph, considering an injected and a basic vortex. The tangential and axial velocity profile of a trailing vortex, as determined with the aid of a three-component hot-wire anemometer system, is shown, and a comparison is conducted regarding the vortex circulation strength calculated from vorticity meter and hot-wire measurements.

Zalay, A. D.

"EXPERIMENTAL INVESTIGATION OF THE DECAY OF A VORTEX PAIR"

M.S. Thesis, June 1970, Mass. Institute of Technology, Cambridge, MA

Simulation, visualization, and qualitative measurements of the decay process of a pair of trailing vortices is outlined in this report. The vortex pair is generated in the laboratory by a tank piston arrangement. A titrated iodine starch solution and electrically pulsed plates are used to create a dark dye locally which is caught up in the vortex core and permits visualization of the decay process. Actual measurements of core size and velocity distribution are made by means of constant temperature hot wire probes and motion pictures. Experimentally measured wave lengths and wave amplitude growth rates for the vortex pair are compared against a linearized model of mutual and self-induction.

Zalay, A. D., White, R. P. W. and Balcerak, J. C.

"INVESTIGATION OF VISCOUS LINE VORTICES WITH AND WITHOUT THE INJECTION OF CORE TURBULENCE"

RASA Report 74-01, February 1974, Rochester Applied Science Associates, Rochester, NY

An experimental research program was conducted to investigate the general characteristics of a line vortex trailed from a three-dimensional lifting surface, and to determine how its general velocity distribution, turbulence level, turbulent frequency content, and dissipation rates are affected by the injection of a jet of turbulent air and by a fixed turbulence generator. Three component hot-wire surveys indicated that injection of the vortex core reduced the peak tangential velocity, established a strong axial flow component, increased the core diameter, altered the turbulence spectrum, and enhanced the turbulence level in the viscous core.

Zalovcik, J. A. and Dunham, Jr., R. E.

"VORTEX WAKE RESEARCH"

Flight Mechanics Symposium on Flight in Turbulence, AGARD, CP-140, 1973, pp. 13-1 to 13-14

Recent NASA investigations of aircraft trailing vortices are reviewed. Some results obtained in flight on vortex characteristics, such as decay of maximum velocity and vortex drift, are presented for distances behind a generating C-5A airplane from 0.6 to 13.0 nautical miles. The lateral control activity of a CV-990 airplane probing the vortices generated by a C-5A airplane is illustrated and the effect of the C-5A aircraft configuration on this activity is indicated. The roll response at various distances behind a generating aircraft and the separation distance for limit controllability of small and medium size aircraft (Cessna 210, Learjet, DC-9, and CV-990) are related to the initial circulation of the generating aircraft. Some results are presented from near-field and far-field studies on accelerated vortex dissipation through the use of various devices such as mass ejection, spoilers, vortex generators, trailing drag devices, and so forth.

Zaman, K. B. M. Q., Fagan, A. F. and Mankbadi, M. R.

"EXPERIMENTAL STUDY OF TIP VORTEX FLOW FROM A PERIODICALLY PITCHED AIRFOIL SECTION"

AIAA Paper 2016-1846, January 2016, San Diego, CA.

An experimental investigation of a tip vortex from a NACA0012 airfoil is conducted in a low-speed wind tunnel at a chord Reynolds number of 40000. Initially, data for a stationary airfoil held at various angles-of-attack are gathered. Detailed surveys are done for two cases: angle of attack of 10 deg with attached flow and angle of attack of 25 deg with massive flow separation on the upper surface. Distributions of various properties are obtained using hot-wire anemometry. Data include mean velocity, streamwise vorticity and turbulent stresses at various streamwise locations. For all cases, the vortex core is seen to involve a mean velocity deficit. The deficit apparently traces to the airfoil wake, part of which gets wrapped by the tip vortex. At small angle of attack, the vortex is laminar within the measurement domain. The strength of the vortex increases with increasing angle of attack but undergoes a sudden drop around angle of attack greater than or equal to 16 deg. The drop in peak vorticity level is accompanied by transition and a sharp rise in turbulence within the core. Data are also acquired with the airfoil pitched sinusoidally. All oscillation cases pertain to a mean angle of attack of 15 deg while the amplitude and frequency are varied. An example of phase-averaged data for an amplitude of ± 10 deg and a reduced frequency of $k=0.2$ is discussed. All results are compared with available data from the literature shedding further light on the complex dynamics of the tip vortex.

Zamyatin, A. N.

"REAL RESEARCH OF DIFFERENT CLASS AIRPLANE VORTEX WAKES AT LOW ALTITUDES"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 45-1 - 45-12.

The paper is intended to investigate airplane wake vortex in real flight at low altitudes. The paper is aimed at obtaining real flight data for wake vortex generation, development and decay processes of an airplane flying at modes approaching the takeoff and landing ones. The acquired data are anticipated to be used in designing means of affecting the wake vortex structures to decrease their unfavorable effects on other flying airplanes, as well as in developing mathematical models of the airplane wake processes. To perform studies special techniques were worked out which allow synchronous measurements of spatial kinematic and geometrical wake characteristics, airplane flight and environmental parameters to be made. The techniques use the hot-wire method for measuring the instant velocity, a method of wake visualization and a stereophotogrammetric survey method. Using these methods, wake vortices of two classes of airplanes were studied: a medium-haul Tu-124 weighing about 35,000 Kgs and a light highly maneuverable L-39 with a weight of 3,500 Kgs. Flights were performed at altitudes below 400 m.

Zamyatin, A. N. and Grachev, V. S.

"FULL-SCALE STUDIES OF STRUCTURE AND DEVELOPMENT OF A VORTEX WAKE OF A MEDIUM TRUNK-ROUTE AIRCRAFT IN THE ATMOSPHERIC BOUNDARY LAYER"

Proceedings of International Council of the Aeronautical Sciences, 14th Congress, Toulouse, France, September 9-14, 1984, pp. 268-273.

This paper describes the developed complex technique, and the results of a full-scale investigation of a vortex wake of a medium trunk-route aircraft are presented. The results of the investigation are the basis for a schematic division of a vortex wake development process into five phases. Qualitative and quantitative characteristics are obtained for each phase of vortex wake development which define the wake structure. The investigation allowed determination of flight parameter and atmospheric condition effects on the vortex wake phase extent.

Zamyatin, A. N., Dedesh, V. T., Kagarmanov, R. L. and Zhelannikov, A. I.

"PECULIARITIES OF AIRPLANE VORTEX WAKES AND CONDENSATION TRAILS INTERACTION AND THEIR MATHEMATICAL MODELING"

Proceedings of the 2nd International Conf. on Transport, Atmosphere and Climate (TAC-2), edited by Sausen, R., van Velthoven, P. F. J., Bruning, C. and Blum, A., June 2009, Aachen, Germany and Maastricht, The Netherlands, pp. 203-216.,

The unique photos, demonstrating air flow peculiarities in aircraft aerodynamic wake vortex, are presented in the report. On the bases of these materials analysis and basing on obtained in flight the quantitative data and calculation wake models results, there are presented the patterns of air flow development and structure in aircraft aerodynamic wake. It is shown that scheme of formed aircraft wake vortex structure could be presented as two independent air flow areas. These areas are separated by closed current surface. First -- more spacious area corresponds to practically plane spiral flows, consisting of two vortices of opposite direction. The second one is in the small area of vortices axis and corresponds to spatial flow with circumferential flow velocities, analogous to solid body rotation and with intensive alternating axial flows. Presented in the report are pictures, obtained in real flight conditions with the help of visualization, demonstrating interaction of wake vortex and contrail for aircraft of different types. It is shown that depending on engine location at the aircraft, the contrail could practically do not interact with aerodynamic wake, mainly being captured by external flow and dissipated at relatively small distances from aircraft. Contrail could also be captured by external vortex flow, then got to vortices nuclei and hold them rather long. Examples of mathematical modeling of a vortex wakes of the airplane, based on MDV utilization are presented in the report, in view of influence of engines jets and conditions of an atmosphere. As an example of wakes calculation for airplanes A-310, A-380 and SSJ-100, the qualitative agreement of results of calculations and visualization of streams in wakes is shown. It indicates a possibility of usage and perfection of this method of calculation for the purposes of model creation, account of wake vortices interaction with contrails both in near and far wake, down to their destruction.

Zamyatin, A. N., Grigoryev, M. A., Rogozin, V. V. and Zhelannikov, A. I.

"MATHEMATICAL MODEL OF AIRCRAFT WAKE VORTICES DEVELOPMENT FOR TAKE-OFF/LANDING PHASES FOR WAKE VORTEX SAFETY SYSTEMS"

ICAS 2014, September 2014, St. Petersburg, Russia.

One of the most important areas of research in aviation technology is an increase of air traffic control efficiency and flight safety provision in vicinity of airfields for take-off/landing flight phases, i.e. in conditions of possible entering of aircraft into wake vortices of other aircraft. Elaboration of wake vortex safety systems (WVSS) is rather effective solution of this problem. Math model of aircraft wake vortex is the main component of WVSS. The model should provide reliable information on intensity and spatial location of dangerous vortices areas. Calculation results should be available in real time scale. Presented in the paper is the detailed description of math model of aircraft wake vortices' development. Examples of calculations of wake vortices characteristics for various aircraft, flight conditions and atmospheric states are presented. It is noted that the model elaborated could be utilized in WVSS both for the take-off/landing flight phases and for cruise flight conditions during aircraft flight along flight routes.

Zare-Noghabi, A. and Shortle, J. F.

"RARE EVENT SIMULATION FOR POTENTIAL WAKE ENCOUNTERS"

Proceedings of the 2017 Winter Simulation Conference, Institute for Operations Research and the Management Sciences, December 2017, Las Vegas, NV, pp. 2554-2565.

A flying aircraft produces two coherent rotating vortices of air in its trail. If another aircraft flies into one of these vortices, it can experience an un-commanded roll. Because of the potential risk, wake separation standards exist to significantly reduce the probability of such events. Thus, wake encounters are inherently rare. As new procedures and technologies are proposed to increase the capacity of the airspace, rare-event simulation is necessary to evaluate to the safety of proposed changes. This paper explores the performance of a rare-event splitting technique in the context of estimating probabilities of potential wake encounters. The goal is to identify good strategies for the splitting method while using a relatively simple model for the wakes. Suggestions for the choice of the level function and the locations of levels are given.

Zatoloka, V. V., Ivanyushkin, A. K. and Nikolayev, A. V.

"INTERFERENCE OF VORTICES WITH SHOCKS IN AIRSCOOPS; DISSIPATION OF VORTEXES"

Fluid Mechanics-Soviet Research, Vol. 7, No. 4, July-August 1978, pp. 153-158.

The dissipation of vortex filaments upon crossing strong shock fronts is described. It is shown that a stagnation zone with a conical shock develops in the free stream. The flow in the detachment zone approaches that which occurs when a turbulent boundary layer is detached from a surface. It is shown that the interference of the vortex filament with the shock in air scoop can have a deleterious effect on performance.

Zavershnev, Y. A., Kushnerev, V. K. and Zamyatin, A. N.

"METHODS OF STUDYING AN AIRPLANE VORTEX WAKE STRUCTURE IN FLIGHTS AT LOW ALTITUDES"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.1, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 21-1 - 21-12.

Vortex wake is a source of hazards for airplanes flying into it, so vortex wake research is urgent. Actual (flight) wake data are the most reliable basis for developing methods to reduce its adverse effects. For civil aviation, of prime interest is the wake effects in flying at low altitudes: just over the runway (0 to 20 m), and in the takeoff and approach area (0 to 300 m). Vortex wake is a rather complex physical phenomenon, the research of which requires a special procedure. The procedure must provide for the following three groups of measurements: the wake characteristics recording, measuring the flight parameters of the airplane generating vortex wakes, and meteorological data acquisition in the wake development region. To estimate wake flow velocity vectors, hot film anemometers were used. To record the vortex core geometry, smoke visualization and stereophotogrammetric survey methods were used.

Zeman, O.

"PROGRESS IN THE MODELING OF PLANETARY BOUNDARY LAYERS"

Annual Review of Fluid Mechanics, Vol. 13, 1981, pp. 253-172.

Comparison of various turbulence-simulation techniques favors second-order modeling as the practical computational method in applications to planetary boundary layers. Still, the complexity of the dynamics of planetary boundary layers presents several challenging problems for second-order modeling. Some of these yet to be resolved are (1) Identification and separation of the surface effects from the effects due to large anisotropy or inhomogeneity on pressure terms (because the near-surface contributions to the pressure terms involve the surface pressure, these contributions could be measured). (2) The effect of stratification on turbulence dynamics near the critical Richardson number. How are the turbulence-energy spectrum and the dissipation rate altered in this stable limit with respect to the neutral conditions? (3) Modeling the effects of large eddy-surface interactions in convective boundary layers by exploring models that allow for anisotropy of turbulence scales and of dissipation partitioning among the energy components. (4) Apart from the theoretical (linear) models, the actual buoyancy contributions in the pressure terms are largely unknown. It would be useful to attempt to identify these buoyancy contributions with the aid of large-eddy or direct turbulence simulations.

Zeman, O.

"THE PERSISTENCE OF TRAILING VORTICES: A MODELING STUDY"

Phys. Fluids, Vol. 7, No. 1, January 1995, pp. 135-143

The principal subject of this paper is analysis and modeling of turbulent wing tip vortex flows in a far-field region of the vortex evolution. The choice of a Reynolds stress closure (RSC) to model the vortex turbulence is shown to be indispensable for representation of the flow rotation effects on turbulence. The principal result reported is the model-experiment comparison of the vortex growth rates for different vortex Reynolds numbers. The mean vortical flow generated by the wing tip very effectively suppresses the Reynolds shear stress, which mediates the extraction of energy from the mean flow by turbulence. In consequence, the vortex-core growth rate is controlled only by molecular viscosity and the vortex turbulence decays since the turbulence production rate is very nearly zero. This rather unexpected result is shown to be supported by experiments. Finally, it is shown that the computed turbulence structure is consistent with experimental data at the NASA Ames Research Center.

Zemtsop, C. P., Stollinger, M. K., Heinz, S. and Stanescu, D.

"LARGE-EDDY SIMULATION OF SWIRLING TURBULENT JET FLOWS IN ABSENCE OF VORTEX BREAKDOWN"

AIAA Journal, Vol. 47, No. 12, December 2009, pp. 3011-3021.

This paper reports the results of numerical investigations of swirling turbulent jet flows by large-eddy simulation. Reynolds-averaged Navier-Stokes simulations are used to generate mean inflow data. Fluctuations are added to the profiles of the means to produce instantaneous inflow data. The instantaneous inflow data are correlated such that the characteristic length and time scales of inflowing turbulent eddies are consistent with the corresponding Reynolds-averaged Navier-Stokes profiles imposed at the inlet. The resulting large-eddy simulation method is validated against experimental data of both swirling and nonswirling turbulent jets. The application of the validated large-eddy simulation method to studies of the mechanism of swirl effects shows the following. Swirl breaks apart the typical ring structures of nonswirling turbulent jets into two modes: a helical mode and streamwise braid structures. The interaction of these two modes generates unorganized turbulence that enhances the turbulent mixing. An analysis of the mixing enhancement by swirl shows a significant increase of the turbulent mixing efficiency of scalars with the swirl number (of up to 21.7 percent for the cases considered).

Zhang, B., Chen, C., Zhu, T., Fu, R. and Xu, P.

"THE INVESTIGATION OF DIFFERENT WING-LETS IMPACT ON WING TIP VORTEX"

Proceedings of the International Conference on Service Robotics Technologies (ICSRT 2018), March 2018, Chengdu, China, pp. 22-26.

In the present work, the formation of the wing-tip vortex from a rectangular NACA0015 wing with a square tip at Re (Reynolds number) = 200,000 and AOA (angle of attack) = 15 degrees were simulated, with a Spalart-Allmaras turbulence model by using of ANSYS FLUENT. Numerical results showed that the wing-lets can break up tip vortex effectively and increase the Lift coefficient, reduce the Drag coefficient. The present study suggested that under the same calculation cost, the most excellent

achievement was grasped with three wing-lets on NACA0015 airfoil at AOA = -15 degrees, the vorticity and drag coefficient reduced by 75% and 9%, respectively, and lift coefficient increased about 27%.

Zhang, B., Song, Z. and Li, J.

"LASER-ULTRASONIC METHOD FOR VORTEX MEASUREMENTS"

Proceedings Third Pacific International Conf. on Aerospace Science and Tech., Shaanxi Science and Tech. Publishing House, Xian, China, September 1997, pp. 5-53

A laser-ultrasonic method is used to measure the vortex flow in wind tunnel tests. The principle of the method is based on the measurement of the flow-induced travel time differences of the ultrasonic signals propagating between two or more laser beams. An advantage of this method is that there is no need to inject particles into the flow field. This method can measure any position in the flow field, including the vortex core. Therefore, the method is used to investigate vortex breakdown and the stability of vortices, and to determine the velocity, vorticity, circulation distribution, and inner structure of a vortex. A test result for the flow field of a ducted fan indicates that this method can obtain the velocity distribution and the swirling structure of this flow field.

Zhang, B., Tang, Q., Chen, L-P. and Xu, M.

"NUMERICAL SIMULATION OF WAKE VORTICES OF CROP SPRAYING AIRCRAFT CLOSE TO THE GROUND"

Biosystems Engineering, Volume 145, March 2016, Pages 52-64.

A study of the velocity field of the wake of a Thrush 510G carrying out spray application close to the ground was investigated. The aircraft normally operates in extreme ground effect and wake vortices play a major role in the dispersal and deposition of pesticide spray released behind the aircraft. The evolution of wake vortices over time, and their interaction with the ground were simulated using computational fluid dynamics (CFD) techniques. The simulation was initialized with meteorological data from a field experiment. Information given by CFD simulation included the trajectory of the wake vortices as well as circulation, which indicates the strength of vortex. This information provided insights into the velocity field in the wake, including the upwash near the wing tips and the downwash in between. The effect of turbulence intensity as well as crosswind on the wake vortices and the resulting velocity field were investigated.

Zhang, H. J., Zhou, Y. and Whitelaw, J. H.

"NEAR-FIELD WING-TIP VORTICES AND EXPONENTIAL VORTEX SOLUTION"

Journal of Aircraft, Vol. 43, No. 2, March-April 2006, pp. 445-449

Vortices shed from the tip of a rectangular half-span wing model (NACA 0012) have been investigated with particle image velocimetry at a chord Reynolds number between $3.4 \times 10,000$ and $26.6 \times 10,000$ and angles of attack = 8 and 16 deg over 0.2 to 5 chord lengths downstream of the model. It has been

found that the measured wing-tip vortex shows little dependence in the circumferential velocity and vorticity, when normalized by their local maximum, on the angle of attack, Reynolds number, and downstream distance from the wing. Furthermore, the radial distributions of circumferential velocity and vorticity coincide quite well with the exponential vortex solution, with only a slight departure outside the core region.

Zhang, M., Cheng, L. and Zhou, Y.

"CLOSE-LOOP CONTROL OF VORTEX - AIRFOIL INTERACTION NOISE"

Journal of Hydrodynamics, Vol. 18, Issue 3, Supplement 1, July 2006, pp. 430-437

Closed-loop controlled interactions between an airfoil and impinging vortices were experimentally investigated. This work aims to minimize the fluctuating flow pressure (p) at the leading edge of the airfoil, which is a major source of the blade-vortex interaction noises commonly seen in rotorcrafts. Piezo-ceramic actuators were used to create a local surface perturbation near the leading edge of the airfoil to alter the airfoil-vortex interaction. Two closed-loop control schemes were investigated, which deployed p and the streamwise fluctuating flow velocity (u) as the feedback signal, respectively. While the control effect on p was measured using a fast response pressure transducer, the oncoming vortical flow was monitored using a particle image velocimetry and a hot wire. It was found that the control scheme based on the feedback signal u led to a pronounced impairment in the strength of oncoming vortices and meanwhile a maximum reduction in p by 39%, outperforming the control scheme based on the feedback signal p . Physics behind the observations is discussed.

Zhang, S.

"NUMERICAL STUDY ON SOUND GENERATION IN THE INTERACTION OF TWO VORTICES"

AIAA Paper No. 2011-0053, January 2011, Orlando, FL.

This is an extension of our previous studies on the shock vortex interaction. Through solving two dimensional unsteady Navier-Stokes equation by a fifth order weighted essentially non-oscillatory schemes (WENO), we systematically studied the interaction between two vortices. Our goal is to reveal the mechanism of sound generation in the interaction between two co-rotating vortices or two counter-rotating vortices. It is found that the interaction of two vortices rely on their strengths and rotating directions. The interaction of two counter-rotating vortices with equal strength generates two vortex poles and three sound waves. While, the interaction between two equally strength co-rotating vortices result in the merging of two vortices at some condition. In the instant of the vortex merging, strong noise are generated. The interaction between two vortices with large difference in their strengths will result in the weak vortex rotating around the stronger one. And strong noise is generated continuously.

Zhang, S., Jiang, S., Zhang, Y.-T. and Shu, C.-W.

"THE MECHANISM OF SOUND GENERATION IN THE INTERACTION BETWEEN A SHOCK WAVE AND TWO COUNTER-ROTATING VORTICES"

Physics of Fluids, Vol. 21, 2009, pp. 076101-1 - 076101-9.

The interaction of a shock wave and two counter-rotating vortices is simulated systematically through solving the two-dimensional, unsteady, compressible Navier-Stokes equations using a fifth order weighted essentially nonoscillatory finite difference scheme. The main purpose of this study is to reveal the mechanism of sound generation in the interaction between a shock wave and two counter-rotating vortices. It is found that there are two regimes of sound generation in this interaction. The first regime corresponds to the shock interaction with two isolated vortices, in which the sound wave generated by the interaction between the shock wave and two counter-rotating vortices equals to the linear combination of the sound waves generated by the interactions between the same shock wave and each vortex. The second regime corresponds to the shock interaction with a coupled vortex pair, in which the sound wave comes from two processes. One is the vortex coupling, and the second is the interaction between the shock wave and the coupled vortex pair.

Zhang, S., Zhang, Y.-T. and Shu, C.-W.

"MULTISTAGE INTERACTION OF A SHOCK WAVE AND A STRONG VORTEX"

Physics of Fluids, Vol. 17, No. 11, November 2005, 116101-1 to 116101-13

The interaction between a shock wave and a strong vortex is simulated systematically through solving the two-dimensional, unsteady compressible Navier-Stokes equations using a fifth-order weighted essentially nonoscillatory finite difference scheme. Our main purpose in this study is to characterize the flow structure and the generation of sound waves of the shock-strong vortex interaction. The simulations show that the interaction of a shock wave and a strong vortex has a multistage feature. It contains the interaction of the shock wave and the initial vortex, of the reflected shock wave and the deformed vortex and of the shocklets and the deformed vortex. The shocklets are generated by the secondary interaction. Due to the complex reflected shock structure, there exist interactions between the reflected shock waves and the sound waves. Many pressure waves are embedded in the second and third sound waves.

Zhang, S.S., Heck, M. and Barthelémy, P.

"MULTI-GPU ACCELERATED WING TIP VORTEX EXTRACTION"

AIAA Paper No. 2011-3678, June 2011, Honolulu, Hawaii.

This paper presents a scientific visualization framework where strong vortical flow features, commonly appearing in turbulence flow, are extracted to support parameterization, automation, and interactive exploration of CFD solutions. Tip vortex near an aerodynamic wing is used as an example to demonstrate how this framework can be used to quantitatively analyze and innovatively visualize large amounts of CFD data. Multiple modern Graphics Processing Units (GPU) are adapted to accelerate both

computing and visualization, with interactive performance achieved even on extremely large mesh. Moreover, algorithmic considerations in precisions and memory management in multi-GPU computing environments suggest broader potential impacts on both simulation solver and post-processing software applications.

Zhang, W., Markfort, C. D. and Porte-Agel, F.

"NEAR-WAKE FLOW STRUCTURE DOWNWIND OF A WIND TURBINE IN A TURBULENT BOUNDARY LAYER"

Experimental Fluids, Vol. 52, 2012, pp. 1219-1235.

Wind turbines operate in the surface layer of the atmospheric boundary layer, where they are subjected to strong wind shear and relatively high turbulence levels. These incoming boundary layer flow characteristics are expected to affect the structure of wind turbine wakes. The near-wake region is characterized by a complex coupled vortex system (including helicoidal tip vortices), unsteadiness and strong turbulence heterogeneity. Limited information about the spatial distribution of turbulence in the near wake, the vortex behavior, and their influence on the downwind development of the far wake hinders our capability to predict wind turbine power production and fatigue loads in wind farms. This calls for a better understanding of the spatial distribution of the 3D flow and coherent turbulence structures in the near wake. Systematic wind-tunnel experiments were designed and carried out to characterize the structure of the near-wake flow downwind of a model wind turbine placed in a neutral boundary layer flow. A horizontal-axis, three-blade wind turbine model, with a rotor diameter of 13 cm and the hub height at 10.5 cm, occupied the lowest one-third of the boundary layer. High-resolution particle image velocimetry was used to measure the velocities in multiple vertical streamwise planes (x-z) and vertical span-wise planes (y-z). In particular, we identified localized regions of strong vorticity and swirling strength, which are the signature of helicoidal tip vortices. These vortices are most pronounced at the top-tip level and persist up to a distance of two to three rotor diameters downwind. The measurements also reveal strong flow rotation and a highly non-axisymmetric distribution of the mean flow and turbulence structure in the near wake. The results provide new insight into the physical mechanisms that govern the development of the near wake of a wind turbine immersed in a neutral boundary layer. They also serve as important data for the development and validation of numerical models.

Zhang, X. and Zerihan, J.

"OFF-SURFACE AERODYNAMIC MEASUREMENTS OF A WING IN GROUND EFFECT"

Journal of Aircraft, Vol. 40, No. 4, July-August, 2003, pp. 716-725

The off-surface aerodynamic characteristics of a wing in ground effect are investigated using several methods including laser Doppler anemometry and particle image velocimetry. The study focuses on two aspects of the flow: turbulent wake and edge vortex. These features are closely associated with the behavior of the aerodynamic force in ground effect. The size of the wake increases in proximity to

the ground. A downward shift of the path of the wake is also observed. Discrete vortex shedding is seen to occur behind the wing. As the wing height is reduced, separation occurred on the suction surface of the wing, and the spanwise vortex shedding is found to couple with a flapping motion of the wake in the transverse direction. An edge vortex is also observed off the edge of the end plate of the wing, which contributes to force enhancement and helps to define the force behavior in the force enhancement region. The rate of change in the downforce vs height curve is linked to the strength of the edge vortex. The vortex breakdown signals a slowdown in the force enhancement. When the maximum downforce height is reached, the edge vortex breaks down completely.

Zhang, X. and Zerihan, J.

"EDGE VORTICES OF A DOUBLE-ELEMENT WING IN GROUND EFFECT"

Journal of Aircraft, Vol. 41, No. 5, September-October 2004, pp. 1127-1137

The influence of edge vortices generated by a generic double-element wing on force behaviors are discussed. The wing is equipped with end plates and operates in ground effect. The downforce-vs-height curve is divided into three distinct regions according to ground proximity and flap setting. As the wing is moved from a height in freestream to the ground plane, the downforce first experiences a rapid enhancement (region A). This process is accompanied by the presence of a concentrated vortex off the edge of the side plate and diffuser effect of the wing. At a critical height, the vortex breaks down and its contribution to the downforce is lost. This creates a change in the gradient of the downforce slope. The force enhancement process continues as the height of the wing is reduced (region B); the main diffuser effect is still present. The downforce is lost below a height where the maximum downforce is reached, due to large separation on the wing (region C). The importance of the edge vortices in defining the characteristics of the downforce curve is established.

Zhang, X., Chung, J. D., Kaplan, C. R. and Oran, E. S.

"A COMPARISON OF IMPLICIT AND EXPLICIT SIMULATIONS OF VORTEX BREAKDOWN"

AIAA Paper 2019-1144, January 2019, San Diego, CA.

Vortex breakdown is an instability which occurs in swirling flows and is seen in both incompressible and compressible flow regimes. The choice of numerical algorithm to compute this flow is critical to resolving the relevant physical phenomena. In previous work, we described the procedure of combining a Barely Implicit Correction (BIC) algorithm with a fourth-order Flux-Corrected Transport (FCT) algorithm to eliminate the sound speed limit for explicit calculations of low-speed flows, and showed that BIC-FCT could predict the three major vortex breakdown modes (spiral, bubble and double-helix). Here, we show a direct comparison of the implicit BIC and explicit FCT algorithms by using the same time step within the explicit stability limit. The comparison is conducted on simulations of a three-dimensional, swirling jet flow with vortex breakdown, by examining the flow structures and examining the property fields. Differences are observed in the phase of the downstream spiral and double-helix

modes. Based on a pressure wave analysis, we attribute this phase shift to the difference of how the explicit FCT and implicit BIC treat an open outflow boundary.

Zhang, X., Wang, Z. and Gursul, I.

"INTERACTION OF MULTIPLE VORTICES OVER A DOUBLE DELTA WING"

AIAA Paper 2015-2308, June 2015, Dallas, TX.

Interactions between strake and wing vortices over a 70-deg/50-deg double delta wing were studied experimentally in a wind tunnel using particle image velocimetry (PIV) measurements. The upstream effect of the wing vortex on the formation of the strake vortex was identified. A dual-vortex structure of the strake vortices is observed before the wing vortex develops. Prior to vortex breakdown, both wing and strake vortices were found meandering in relatively small regions. The correlation between the instantaneous locations of the vortices increases if the vortices become sufficiently close to each other. The proper orthogonal decomposition (POD) analysis of the instantaneous velocity fields suggested that, for both wing and strake vortices, the most energetic mode was displacement in the first helical mode. The most energetic mode reveals out-of-phase displacements when the vortices are close to each other.

Zhang, X., Zerihan, J., Ruhrmann, A. and Deviese, M.

"TIP VORTICES GENERATED BY A WING IN GROUND EFFECT"

11th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 2002

Tip vortices generated by a cambered, single element wing operating in ground effect were studied using a range of methods including particle image velocimetry (PIV), laser Doppler anemometry (LDA), surface pressures, force balance measurements, and surface flow visualization. The wing was placed suction surface down, leading to down-force and a complex system of trailing vortices evolving in proximity to the ground. The characters of the tip vortex led to changes in the aerodynamic force behavior in ground effect. The down-force was found affected by the presence of separation on the suction surface and the tip vortices. At larger ground heights, a concentrated tip vortex was produced off the edge of the endplate on the wing through separation, contributing to the down-force enhancement process. The tip vortex induced an upwash on the wing, leading to an effective reduction in the incidence of the wing and hence smaller extents of separation near the wing tip. However, vortex breakdown occurred as the wing was lowered to the ground, leading to a slowdown in the force enhancement.

Zhang, Y.

"AFS-450 SIMULATION CAPABILITY DEVELOPMENT NATIONAL AIRSPACE SYSTEM STOCHASTIC SIMULATION PHASE III WAKE ENCOUNTER MODEL RESEARCH AND PLANNING"

DOT-RITA-RVT-72-10-02-1.0, February 2010, US DOT Volpe National Transportation Systems Center, Cambridge, MA.

The Volpe Center has developed the Vehicle Simulation Tool (VST) for the Flight Systems Laboratory (AFS-450) of the FAA. The VST is used for safety studies and validations of aircraft traffic during landing and/or takeoff operations. The Phase III development of the VST is planned to add the Wake Vortex Encounter (WVE) model to enhance the model capability for evaluating the influence of air traffic safety due to the interaction of aircraft and wake vortex. The prototype of the WVE tool has been developed to provide an off-line tool to create mathematical functions that statistically model aircraft responses during the wake encounter. The tool uses X-Plane as the high-fidelity aircraft flight simulator and collects the data of the aircraft state vector (altitude, roll angle, acceleration, etc.) during the flight. By using multi-variable Least Square Method, closed-form mathematical formulas are generated for the WVE model that are computationally efficient. This report presents the wake model research and planning for Phase III VST. The preliminary design and results of the WVE model are presented. Each aircraft in the model is considered as a source that generates wake and also as a following aircraft that may encounter the wake generated by other aircraft. The model interacts with the flight simulator (such as the VST) in two ways: (1) by taking aircraft flight data in real-time during the flight simulation, and (2) by post-processing the data file generated by the flight simulator which shows the time histories of aircraft locations. The reports generated by the WVE model will contain information of wake encounter time, location, wake encounter geometry, maximum and deviation of aircraft state change.

Zhang, Y. and McGovern, S.

"PARAMETRIC STUDY OF AIRCRAFT RESPONSE DUE TO WAKE VORTEX ENCOUNTER"

IEEE/AIAA 29th Digital Avionics Systems Conference, Oct. 2010, Salt Lake City, Utah.

A simulation-based tool which creates mathematical functions that statistically model aircraft responses during various user-selectable wake encounters is presented. A wake vortex is created due to aircraft wings moving through the viscous air. The methods currently available to minimize the influence of wake vortices on the trailing aircraft can often impact airport capacity. As such, it is of interest to quantify the effect of different size wakes at different encounter geometries and with different aircraft types, flight configurations, speeds, and altitudes. By collecting simulation results generated using a high-fidelity computational-fluid-dynamics-based aircraft flight model combined with industry, government, and academic wake models, numerous encounter aircraft responses (e.g., pitch,

roll, Gs, altitude deviation, etc.) can be calculated. Using the multi-variable least squares method, closed-form mathematical formulas can then be generated from the simulation results to allow for the calculation of other wake encounter situations. This paper presents the preliminary design and gives results from the simulation tool and the associated post-processing for generation of the wake encounter equations and their aircraft-type-specific coefficients. A simple case study is then presented to demonstrate some typical results.

Zhang, Y., Rudis, R. P., Wang, F. Y. and Spitzer, E. A.

"SIMULATION OF JET BLAST EFFECT ON LANDING AIRCRAFT"

Air Traffic Control Quarterly, Vol. 9, No. 3, 2001, pp. 211-227.

In this paper, we describe a computer simulation of the jet blast effect on an aircraft landing on an orthogonal runway. A phenomenological jet blast model is first presented, followed by a study of its effect on a landing aircraft passing through the blast region. The jet blast issued from the departing aircraft in motion is simplified as a cosine function, specified by peak velocity and width. The jet blast velocity is assumed to cause an additional sideslip velocity for the landing airplane, whose value is subsequently modified accordingly to the coupled governing flight dynamics equations. Numerical simulations are conducted for two different landing aircraft under the control of an automatic landing system.

Zhang, Y., Shortle, J. and Sherry, L.

"COMPARISON OF ARRIVAL TRACKS AT DIFFERENT AIRPORTS"

Proceedings of 4th International Conference on Research in Air Transportation, ICRAT 2010, June 2010, Budapest, Hungary.

This paper analyzes arrival track data at Chicago (ORD) and Atlanta (ATL) airports. We investigate distributions of vertical and lateral position at different distances from the runway threshold in instrument meteorological conditions (IMC) and visual meteorological conditions (VMC). In IMC, the observed standard deviations at different distances are similar between the two airports. The results reported in this paper are also like those reported at St. Louis (STL). Visual comparison of the observed distributions also shows a close similarity. This provides some indication that distributions observed at one airport in IMC may generalize to other airports. In VMC, there are some differences between the distributions. We also fit probability density functions to lateral and vertical positions. In general, the normal distribution provides the best fit among the normal, lognormal, gamma, and Weibull families. The quality of the fit is better in IMC closer to the runway threshold.

Zhang, Y., Wang, F. Y. and Hardin, J. C.

"SPECTRAL CHARACTERISTICS OF WAKE VORTEX SOUND DURING ROLL-UP"

NASA-CR-2003-212673, December 2003, NASA Langley Research Center, Hampton, VA

This report presents an analysis of the sound spectra generated by a trailing aircraft vortex during its rolling-up process. The study demonstrates that a rolling-up vortex could produce low frequency (less than 100 Hz) sound with very high intensity (60 dB above threshold of human hearing) at 200 feet from the vortex core. The spectrum then drops off rapidly thereafter. The study suggests that acoustic sensors operating at low frequency band could be profitably deployed for detecting the vortex sound during the rolling-up process.

Zhao, J.

"DYNAMIC WAKE DISTORTION MODEL FOR HELICOPTER MANEUVERING FLIGHT"

PhD Thesis, March 2005, Georgia Institute of Technology, Atlanta, GA.

A new rotor dynamic wake distortion model, which can be used to account for the rotor transient wake distortion effect on inflow across the rotor disk during helicopter maneuvering and transitional flight in both hover and forward flight conditions, is developed. The dynamic growths of the induced inflow perturbation across the rotor disk during different transient maneuvers, such as a step pitch or roll rate, a step climb rate and a step change of advance ratio are investigated by using a dynamic vortex tube analysis. Based on the vortex tube results, a rotor dynamic wake distortion model, which is expressed in terms of a set of ordinary differential equations, with rotor longitudinal and lateral wake curvatures, wake skew and wake spacing as states, is developed. Also, both the Pitt-Peters dynamic inflow model and the Peters-He finite state inflow model for axial or forward flight are augmented to account for rotor dynamic wake distortion effect during helicopter maneuvering flight. To model the aerodynamic interaction among main rotor, tail rotor and empennage caused by rotor wake curvature effect during helicopter maneuvering flight, a reduced order model based on a vortex tube analysis is developed. Both the augmented Pitt-Peters dynamic inflow model and the augmented Peters-He finite state inflow model, combined with the developed dynamic wake distortion model, together with the interaction model are implemented in a generic helicopter simulation program of UH-60 Black Hawk helicopter and the simulated vehicle control responses in both time domain and frequency domain are compared with flight test data of a UH-60 Black Hawk helicopter in both hover and low speed forward flight conditions.

Zhao, J. and He, C.

"ENHANCEMENT OF VISCOUS VORTEX PARTICLE METHOD FOR FUNDAMENTAL ROTOR WAKE DYNAMICS SIMULATION"

AIAA Paper No. 2012-1196, January 2012, Nashville, Tennessee.

This paper describes the investigation of the fundamental physics of rotor wake dynamics, including the essential properties of the rotor tip vortices, such as the trajectory, the core size, the circulation strength, etc. The paper also discusses the simulation of the challenging rotor aerodynamic interference problems using the state-of-the-art viscous Vortex Particle Method (VPM). In order to

accurately model the complicated rotor wake problem, efforts were made to enhance the viscous vortex particle method, including the multi-resolution vorticity source generation, the VPM-VIC algorithm, and the far field boundary conditions. This paper also addresses the aerodynamic interaction to allow for the effects of the near field structures, such as the fuselage and the ship deck. Simulation results were compared with available measurements and excellent correlations were demonstrated.

Zhao, Q.-J., Xu, G.-H. and Zhao, J.-G.

"NEW HYBRID METHOD FOR PREDICTING THE FLOWFIELDS OF HELICOPTER ROTORS"

Journal of Aircraft, Vol. 43, No. 2, March-April 2006, pp. 372-380.

Based on a Navier-Stokes/full potential/free wake solver, a new hybrid method was developed for efficient predictions of the three-dimensional viscous flowfield of a helicopter rotor under both hover and forward flight conditions. The developed flow solver was composed of three modules: 1) a compressible Navier-Stokes analysis to model the viscous flow and near wake about the blade, 2) a compressible potential flow analysis to model the inviscid isentropic potential flow region far away from the rotor, and 3) a free wake model to account for tip vortex effects once the tip vortex leaves the viscous flow region and enters the potential flow region. In this hybrid method, a moving embedded grid methodology was adopted that accounts for rigid blade motions in rotation, flapping, and pitching. A dual-time method was employed to fulfill the calculation of the unsteady flowfields of helicopter rotors, and a third-order upwind scheme (MUSCL) and flux-splitting scheme without introducing artificial viscosity were used to calculate the flux. To search suitable donor elements in embedded grids to pass information between the viscous flow and potential flow zones, a new searching scheme was implemented. The sectional pressure distributions of a UH-60A helicopter rotor and an AH-1G model rotor in hover and forward flight, with and without the wake model, were calculated, and the developed hybrid model was validated by comparing with available experimental data. The simulated steady and unsteady lifting results of a model rotor with three different blade-tip planforms demonstrate the benefits of the curvilinear swept tip and constant swept tip in suppressing supercritical flows.

Zhelannikov, A. I.

"TO THE STUDY OF WAKE VORTEX BEHIND THE AIRBUS-380 CHARACTERISTICS AT TAKEOFF AND LANDING"

Civil Aviation High Technologies, Vol. 19, No. 6, 2016, pp. 51-57. [In Russian]

Every year new aircraft emerge in civil aviation. The wide-body A-380 aircraft with a take-off weight of up to 560 t has come to operation recently. The wake vortex behind such plane poses a real threat for other planes. Such wake is especially dangerous during weak cross wind at takeoff and landing. Vortex wake behind the A-380 plane characteristics research using the developed computing software has been executed in this article. Design-software complex includes two mathematical models, the

mathematical model of the close wake vortex and the mathematical model of the distant wake vortex. These mathematical models are based on the vortex method. A mathematical model of the close wake vortex is based on the analytical-experimental approach. At cruising flight regimes, it is a four-vortex system wake vortex, and at takeoff and landing regimes it is six- or eight-vortex system. A mathematical model of the far wake vortex is based on the exact solution of the Helmholtz equations. This allows consideration of the vortex diffusion and dissipation over time. The influence of the axial velocity in the mathematical model of the distant wake vortex is given by placing it in the center of the vortex flow. Its intensity is found from the experimental data. Calculated fields are perturbed velocities for the A-380 aircraft. Fields of the indignant speeds at a light cross wind of 0.5 m/s - 1.5 m/s in various time points are presented. The moments at which there is a wing vortex lag of the A-380 plane over very center of runway are shown. Calculation of aerodynamic characteristics of the MC-21-400 plane in the vortex trace of the A-380 plane is executed. It is shown when the MC-21-400 plane gets in to the center of a wing vortex, the arising moments of the roll are not parried.

Zhelannikov, A. I.

"FEATURES OF SPREAD OF VORTEX WAKE BEHIND AIRCRAFT AT TAKEOFF AND LANDING, IF CROSSWINDS"

Civil Aviation High Technologies, No. 223, 2016, pp. 5-11.

With commercially-developed software system, carried out research on the impact of crosswinds on the position of vortex wake at takeoff and landing of aircraft of various classes. Identified the threat, in terms of 'hovering' of wing vortex over the center of the runway, versus crosswind speed. During takeoff and landing aircraft, these vortices can be a danger to other aircraft. [In Russian..

Zheltovodov, A. A., Pimonov, E. A. and Knight, D. D.

"SUPERSONIC VORTEX BREAKDOWN CONTROL BY ENERGY DEPOSITION"

AIAA Paper No. 2005-1048, Reno, NV, January 2005

A possibility for using steady and periodic pulse energy deposition to stimulate a vortex breakdown in conditions of its interaction with an oblique shock wave is demonstrated on a basis of the numerical computations in the framework of the nonstationary Euler equations. The vortex/oblique shock wave interaction (VOSWI) at Mach numbers 3 and 5 is analyzed. It is shown that the formation of a subsonic wake downstream of an energy source lying on the vortex axis contributes to a more significant growth of the dimensions of the arising recirculation zone as compared to the cases when the vortex core remains supersonic. The growth of the streamwise velocity deficiency on the vortex axis contributes to an earlier vortex disintegration on the shock in conditions of energy deposition. An increased flow unsteadiness is revealed at the early stages of the vortex breakdown formation in conditions of periodic pulsed energy deposition, which stimulates the shock front waviness. The flowfield structure for different regimes of VOSWI with steady and periodic pulsed energy deposition is analyzed. The

analogies between the vortex breakdown and turbulent separation are specified on the basis of numerical and experimental data as well as theoretical analysis.

Zhelotovodov, A. A., Pimonov, E. A. and Knight, D. D.

"VORTEX BREAKDOWN SIMULATION BY THE STEADY AND PERIODIC PULSE ENERGY DEPOSITION IN A VICINITY OF SHOCK WAVE"

AIAA Paper No. 2006-0401, January 2006, Reno, NV.

The vortex/oblique shock wave interaction (VOSWI) at the Mach numbers 3 and 5 is analyzed on a basis of the numerical computations in a framework of the 3-D nonstationary Euler equations. A possibility of the vortex breakdown control using steady and periodic pulsed energy deposition is demonstrated in the cases of weak, moderate, and strong regimes of VOSWI. Influence of the energy sources of spherical and ellipsoidal geometry, their dimensions and location on the vortex axis as well as the energy deposition power and frequency is considered. The specific details of the realized flowfield structures are analyzed. The correlations for the plateau pressure level in the vortex breakdown zones and the near-wall boundary layer separation regions are considered.

Zhelotovodov, A. A., Pimonov, E. A. and Knight, D. D.

"NUMERICAL MODELING OF VORTEX/SHOCK WAVE INTERACTION AND ITS TRANSFORMATION BY LOCALIZED ENERGY DEPOSITION"

Shock Waves, Vol. 17, 2007, pp. 273-290.

Three-dimensional unsteady Euler simulations are presented for the interaction of a streamwise vortex with an oblique shock of angle 23.3 degrees at Mach 3 and 5. The flowfield features are analyzed for weak, moderate and strong interaction regimes. The details of the free recirculation zone at conditions of subsonic and supersonic flow on the vortex axis are considered. The vortex breakdown under conditions of a subsonic vortex core is characterized by a continuous growth and gradual degeneration of the region, unlike the supersonic core condition wherein a steady recirculation zone is achieved. The possibility of using a localized steady and pulsed periodic energy deposition on the vortex axis for stimulating the breakdown is demonstrated for various interaction regimes. It is shown that the formation of a subsonic wake downstream of an energy source lying on the vortex axis contributes to a more significant growth of the dimensions of the recirculation zone compared to the case when the vortex core remains supersonic. The possibility of achieving the effects similar to the steady case is demonstrated by the effect of a pulsed periodic energy source on the flow under consideration for corresponding equivalence parameters.

Zheng, K., Tian, W., Qin, J. and Hu, H.

"INVESTIGATION OF WIND TURBINE WAKES OVER COMPLEX TERRAIN BASED ON ACTUATOR DISK METHOD"

AIAA Paper 2017-4073, June 2017, Denver, CO.

As wind energy in flat terrain have been exploited, sites in complex terrain is becoming more attractive. However, the topographic effect makes the installation in complex confront great difficulty. One of the problems is the wind farm layout optimizations as a lack of accurate, computational tractable wake model. In order to found a suitable model considering the topographic effect, the numerical investigation of wind turbine wakes over complex terrain is presented in this paper. The method is based on the actuator disk theory and is validated with the experimental data. The result indicates that the deficit at hub height is not monotonously decreasing as the wind turbine sited in front of the hill for gentle slope without flow separation, and the turning point is on the hilltop. The wake center height doesn't change obviously as wind turbine sited on the hilltop, while it has an evident change for other locations of wind turbine. For steep slope with flow separation, the wind turbine in front of the hill can decrease the separation region, while the turbine on the hilltop has no evident effect on the flow separated. It is likely because that the wake improves the turbulence intensity, which is good for the velocity recovery. The flow separation makes the wake characteristic different from that without separation, and there is need to study farther about the terrain with steep slopes.

Zheng, Y. and Ramaprian, B. R.

"AN EXPERIMENTAL STUDY OF WING TIP VORTEX IN THE NEAR WAKE OF A RECTANGULAR WING"

MME-TF-93-1, June 1993, Washington State University, Pullman, WA.

An experimental study of the tip vortex behind a NACA 0015 rectangular wing of aspect ratio 4 was carried out to understand the structure and evolution of the vortex in the near-wake region. The results of these experimental studies are presented in this report. These measurements were made nonintrusively using three-component laser-Doppler velocimetry (LDV). The experiments were carried out at a Reynolds number of about 180,000 in a low-speed wind tunnel. Two cases were studied, namely, (i) stationary wing and (ii) wing oscillating in pitch sinusoidally about its quarter-chord axis. The flow properties measured were the three components of the instantaneous velocity. These data were processed to obtain time-mean and phase-locked flow properties such as velocity, vorticity and turbulence. The data were obtained at several locations at 0.15 - 3.0 chord lengths downstream from the trailing edge. The typical distributions of mean velocity, vorticity, circulation, and turbulent intensity in the near wake are presented and discussed for the stationary wing. In the case of the oscillating wing, the phase-locked velocity, vorticity and turbulence data show details of the evolution of the unsteady tip vortex downstream from the trailing edge. The results also show that the flow is strongly non-quasi-steady at the oscillation frequency studied. The results are fully archived on tape and are available to any interested reader. These can be used as database in the development of wake models for the finite wing, and in studies of three-dimensional wing aerodynamics.

Zheng, Z. C.

"A CONSISTENT BOUNDARY CONDITION FOR VORTICITY-STREAMFUNCTION SIMULATIONS OF WALL-BOUNDED VORTEX FLOWS"

In: Numerical Methods in Laminar and Turbulent Flow, Vol. 9, Pt. 1; Proceedings of the 9th International Conference, Atlanta, GA, Pineridge Press, 1995, pp. 179-190

This paper was motivated by an ongoing computational effort to model the aircraft wake vortex hazard near airports. Those flows can usually be approximated as a pair of 2D incompressible vortices interacting with an infinite solid wall. The present numerical model uses a vorticity-streamfunction formulation to simulate the 2D problem. Since vorticity generation near the wall alters the evolution of the secondary and tertiary vortices directly, accurate modeling of the wall region is critical. A local relationship between vorticity and streamfunction for a wall boundary condition has been established from a new point of view by specifying the streamfunction at the boundary grid lifted away from the solid wall. The new method has utilized Taylor series expansions near the wall boundary. Although the resulting expressions are only first order accurate, the critical importance of physical and mathematical consistency has been achieved. Numerical test cases are discussed in the paper.

Zheng, Z. C.

"THE INFLUENCE OF REYNOLDS NUMBER AND ATMOSPHERIC EFFECTS ON AIRCRAFT WAKE VORTICES NEAR THE GROUND"

Ph.D. Thesis, 1993, Old Dominion University, Norfolk, VA

Aircraft wakes represent potential hazards which can control aircraft spacing and thus limit airport capacity. Wake vortex trajectories and strengths are altered radically by interactions with the ground plane and by atmospheric conditions. This work has been concerned with developing more accurate numerical predictions. A two-dimensional, unsteady numerical-theoretical study is presented which has included viscous effects, the influence of stratification, crosswind and turbulence on vortex behavior near the ground plane, using a vorticity-streamfunction formulation. A two-parameter perturbation procedure has been developed which uses analytic solutions for the initial flow field to accommodate the ground effect region in the numerical simulation. Using an order of magnitude analysis, it was possible to justify the Boussinesq approximations for turbulent wake vortex predictions, including ground effects and atmospheric stratification. It has been shown that the eddy-viscosity turbulence models were not effective in predicting wake vortex flows and a Reynolds stress transport model was implemented. The numerical solutions to the Navier-Stokes equations have been compared with experimental results for the laminar, unstratified cases and good agreement has been obtained. The computational simulations show that the vortex rebound near the ground plane is caused by ground boundary-layer separation. High stratification levels can confine the motion of the vortex system and alleviate the primary vortex strength. Vortex turbulence influences vortex trajectories more strongly than it influences the rate of change in vortex strength. Weak crosswinds cause the upstream primary vortex to rebound less strongly than the downstream vortex. Finally, suggestions are made for future research.

Zheng, Z. C.

"FAR-FIELD ACOUSTIC PRESSURE FROM A SYSTEM OF DISCRETE VORTICES WITH TIME-VARYING CIRCULATION"

AIAA Paper No. 2005-3005, Monterey, CA, May 2005

Primary fluid dynamic sources of sound are from vortices. In problems such as aircraft high-lift noise and wake-vortex sound, vortex methods have been selected as modeling tools for the fluid dynamic processes. In order to use the results from vortex methods for sound generation predictions, it is necessary to relate the near-field vorticity to the far-field acoustic parameters. A theoretical development following an asymptotic expansion method is presented that results in a relation between the vortex impulse and the far-field sound. The formula, which includes the effect of time-varying vortices, can be considered as a two-dimensional representation of Powell's and Mohring's equations. An example of a pair of decaying, counter-rotating vortices is used to apply the formula to calculate the far-field sound of the vortex system.

Zheng, Z. C.

"THIN-TUBE VORTEX SIMULATIONS FOR SINUSOIDAL INSTABILITY IN A COUNTER-ROTATING VORTEX PAIR"

International J. for Numerical Methods in Fluids, Vol. 39, June 2002, pp. 301-324

A thin-tube vortex method is developed to investigate the intrinsic instability within a counter-rotating vortex pair system and the effects from the core size and the wavenumbers (or wavelengths). The numerical accuracy and the advantages of the scheme are theoretically estimated. A nearest-neighbor image method is employed in this three-dimensional vortex simulation. Agreement with Crow's instability analysis has been achieved numerically for the long-wave cases. A short-wave instability for the zeroth radial mode of bending instability has also been found using the thin-tube vortex simulations. Then, the combinations of long- and short-wave instability are investigated to elucidate the non-linear effects due to the interactions of two different modes. It is shown that instability is enhanced if both long- and short-wave instabilities occur simultaneously. Although the method used in the paper is not capable of including effects such as axial flow, vortex core deformation and other complicated viscous effects, it effectively predicts and clarifies the first-order factor that dominates the sinusoidal instability behaviour in a vortex pair.

Zheng, Z. C.

"THE EFFECTS OF ATMOSPHERIC TURBULENCE ON AIRCRAFT WAKE VORTICES NEAR THE GROUND"

AIAA Paper No. 1996-1954, New Orleans, LA, June 1996

A second-order-closure turbulence model has been used to study the effects of atmospheric turbulence on the behavior of aircraft wake vortices near the ground. The numerical simulations have been compared with flight measurement data and good agreement has been obtained. The results show that atmospheric turbulence levels have more significant influence on vortex decay histories than on its transport behavior. Although simple turbulence models are more practical for vortex hazard forecasts in terms of computational overhead, second-order closure models are shown to be the minimum level turbulence model to simulate properly the flow physics such as centrifugal effects near vortex cores and the phase shift between the shear strain and the turbulent shear stress.

Zheng, Z. C.

"BETZ INVARIANTS AND GENERALIZATION OF VORTICITY MOMENT INVARIANTS"

AIAA Journal, Vol. 39, No. 3, March 2001, pp. 431-437

The widely used Betz invariants can be categorized as invariants of vorticity moments or impulses in plane motion for mostly inviscid vortex flow. These invariants have served as a foundation of vortex roll-up process analysis as well as benchmarks to estimate numerical simulation errors for vortex flow. The analysis starts from a more general integral divergence relation in rational mechanics to extend the analysis for both inviscid and viscous vortex flow cases, with or without finite boundaries. Conditions for the existence of the Betz invariants and their extensions to include viscous effects are discussed. These extensions can be used as analytical means for theoretical modeling of complicated vortex systems, especially in flows with viscous effects and finite boundaries. The goal of this study is to clearly establish when the Betz invariants and the generalized vorticity moment invariants are applicable. The approach uses rigorous mathematical analysis, and the physical interpretations of the results are discussed. A trailing vortex pair is used as an example to illustrate the applications of the theoretical study.

Zheng, Z. C.

"INITIALIZATION AND SIMULATION OF THREE-DIMENSIONAL AIRCRAFT WAKE VORTICES"

AIAA Paper No. 1997-2264, Atlanta, GA, June 1997

This paper studies the effects of axial velocity profiles on vortex decay to properly initialize and simulate three-dimensional wake vortex flow. Analytical relationships are obtained based on a single vortex model and computational simulations are performed for a rather practical vortex wake, which show that the single vortex analytical relations can still be applicable at certain streamwise sections of three-dimensional wake vortices.

Zheng, Z. C.

"INFLUENCE OF ATMOSPHERIC TURBULENCE ON CROW-TYPE INSTABILITY OF A VORTEX IN GROUND EFFECT"

AIAA Paper 2013-2550, June 2013, San Diego, CA.

Crow instability of a pair of counter-rotating vortices in free space is extended to study the case of a single vortex interacting with its ground image when the vortex is in ground effect. The atmospheric turbulence condition triggers and enhances the instability and can potentially cause 'linking' of the vortex to the ground. An analytical model is employed to investigate the growth rate and standing-wave angle under different intensity and wave number of atmospheric turbulence.

Zheng, Z. C. and Ash, R. L.

"PREDICTION OF TURBULENT WAKE VORTEX MOTION NEAR THE GROUND"

Transitional and Turbulent Compressible Flows, edited by L. D. Kral and T. A. Zang, ASME Fluids Engineering Conference, Washington, DC., ASME, FED Vol. 151, 1993, pp. 195-207.

Various eddy viscosity turbulence models were compared with a Reynolds stress transport model for predicting the behavior of a two-dimensional vortex pair in ground effect. This study determined that the eddy viscosity models were not effective in predicting these flows and a Reynolds stress transport model was implemented. Subsequently, we have investigated the motion of a simulated aircraft wake vortex pair in ground effect at circulation-based Reynolds numbers of up to 75,000. Using an order or magnitude analysis, it was possible to justify the Boussinesq approximations for turbulent wake vortex predictions including ground effects and atmospheric stratification.

Zheng, Z. C. and Ash, R. L.

"VISCOUS EFFECTS ON A VORTEX WAKE IN GROUND EFFECT"

Proceedings of the Aircraft Wake Vortices Conf., DOT/FAA/SD-92/1.2, DOT Volpe National Transportation Systems Center, Cambridge, June 1992, pp. 31-1 - 31-30

Wake vortex trajectories and strengths are altered radically by interactions with the ground plane. Prediction of vortex strength and location is especially important in the vicinity of airports. Simple potential flow methods have been found to yield reasonable estimates of vortex descent rates in an otherwise quiescent ambient background, but those techniques cannot be adjusted for more realistic ambient conditions and they fail to provide satisfactory estimates of ground-coupled behavior. The authors have been involved in a systematic study concerned with including viscous effects in a wake-vortex system which is near the ground plane. The study has employed numerical solutions to the Navier-Stokes equations, as well as perturbation techniques to study ground coupling with a descending vortex pair. Results of a two-dimensional, unsteady numerical-theoretical study are presented in this paper. A time-based perturbation procedure has been developed which permits the use of analytical solutions to an inner and outer flow domain for the initial flowfield. Predictions have been compared with previously reported laminar experimental results. In addition, the influence of stratification and turbulence on vortex behavior near the ground plane has been studied.

Zheng, Z. C. and Ash, R. L.

"STUDY OF AIRCRAFT WAKE VORTEX BEHAVIOR NEAR THE GROUND"

AIAA Journal, Vol. 34, No. 3, March 1996, pp. 580-589

Aircraft wake vortices have been modeled using an unsteady, two-dimensional laminar (constant eddy viscosity) approximation of the Navier-Stokes equations, to study the influence of ground coupling, stratification, and crosswind on vortex system behavior and decay. Initialization and boundary conditions are developed and implemented systematically for a nonuniform grid representation of the semi-infinite domain containing a vortex pair. Subsequently, the physics of wake vortex interactions with the ground for different types of surface weather conditions are discussed.

Zheng, Z. C. and Baek, K.

"INVISCID INTERACTIONS BETWEEN WAKE VORTICES AND SHEAR LAYERS"

J. Aircraft, Vol. 36, No. 2, March-April 1999, pp. 477-480.

An inviscid vortex simulation showed that the shear-layer deformation causes the vortex descent history difference in the two vortices of a trailing vortex pair. Because of the interactions between the vortices from the shear layer and the vortex pair, the induced velocities on the vortex pair have been changed. Such changes produce different trajectories when the vortex pair is interacting with a concentrated shear layer below or above it. The results show that if a shear layer is put below the vortex pair containing shear vortices with the same sign as the left vortex, the right vortex descends less than the left vortex. When the same shear layer is set above the vortex pair, the right vortex descends more. The descent altitude difference increases with the shear-layer strength. The two vortices do not show altitude difference when they go through a constant, nondeformed shear layer.

Zheng, Z. C. and Baek, K.

"SHEAR-LAYER EFFECTS ON TRAILING VORTICES"

AIAA Paper No. 1998-0316, Reno, NV, January 1998

Crosswind shear can influence the trailing vortex trajectories significantly, according to both field measurement and numerical simulations. Point vortex models are used to study the fluid dynamic mechanism in the interactions between trailing vortex pair and shear layers. It has been shown that the shear-layer deformation causes the vortex descent history difference in the two vortices of the vortex pair. When a shear layer is below the vortex pair with the same sign as the left vortex, the right vortex descends less than the left vortex. When the same shear layer is above the vortex pair, the right vortex descends more. The descent altitudes of the two vortices are the same when they go through a constant, non-deformed shear layer. Those trends are in agreement with Navier-Stokes simulations.

Zheng, Z. C. and Baek, K.

"N-S SIMULATIONS OF CROW-TYPE INSTABILITIES IN VORTEX WAKE"

AIAA Paper No. 1999-0981, Reno, NV, January 1999

Three-dimensional Navier-Stokes simulations of the Crow instability of wake vortices are conducted using large-eddy simulations without background turbulence. Sinusoidal displacement has been specified as the initial perturbation for the vortex system. The results have shown that the minimum Crow instability wavelength is about one vortex spacing shorter than predicted by Crow's linear stability theory. The planar-standing-wave-angle value and the amplitude indifference behavior agree with Crow's analysis. Simulations with periodicity in the axial direction have indicated minor influence of axial flow on the Crow instability.

Zheng, Z. C. and Budlong, D. D.

"INTERACTIONS BETWEEN VORTICES AND SECONDARY VORTICAL STRUCTURES"

AIAA Paper No. 1999-3284, Norfolk, VA, June-July 1999

A vortex method is developed to investigate the intrinsic instability within the primary counter-rotating vortex pair system and the influence from the secondary structure such as vortex rings contouring the vortex pair. Agreement with Crow's instability analysis has been achieved numerically. Both steady and decayed disturbances from the ring structure have been simulated. The long-wave mode disturbances from the rings can develop differently from the long-wave sinusoidal disturbances in the vortex pair, while the short-wave mode disturbances stay neutrally stable.

Zheng, Z. C. and Hardin, J. C.

"IMPORTANCE OF ANTISYMMETRIC MODES OF THE CROW INSTABILITY"

AIAA Journal, Vol. 55, No. 7, July 2017, pp. 2123-2128.

The antisymmetric mode was neglected in the original Crow instability. In this study, a general-instability-analysis method was used to obtain the upper bounds of the instability growth rates, which are independent of the cutoff parameter in the self-induction integral. This result suggests that, not only do the antisymmetric modes exist, but also they are most amplified. These antisymmetric modes can occur in both the long- and short-wave modes. An example of the growth histories of the symmetric and antisymmetric modes for an aircraft wake is given. It is shown that the presence of the antisymmetric modes can cause the time of linking of the wake vortices to be shortened, which could lead to the reduction of the wake-vortex hazard to following aircraft.

Zheng, Z. C. and Li, W.

"FREQUENCY DEPENDENCE ON CORE DYNAMICS IN MULTIPLE VORTEX INTERACTIONS"

AIAA Paper No. 2007-3415, Rome, Italy, May 2006

In a vortex system with multiple vortices such as a complicated aircraft vortex wake, the sound emission frequency of the unsteady vortex core is subjected to change because of interactions between multiple vortices. The behavior of the influence, indicated by the ratio between the core size and the distance of the vortices, and the underlining vortex core dynamic mechanisms are investigated. A vortex particle method is used to simulate the vortex core dynamics in two-dimensional, inviscid and incompressible flow. The flow field, in the form of vorticity, is employed as the source in the far-field acoustic calculation using a vortex sound formula. Cases of co-rotating vortices and a multiple-vortex system composed of two counter-rotating vortex pairs are studied for applications to aircraft wake vortex sound. The study shows, without vortex merging, individual frequencies can be clearly identified that are due each to core rotation (self-induction) and co-rotating motion of a vortex center around the other (mutual induction). The ratio of the core size and the distance between vortices does not seem to significantly influence the frequency of vortex core rotation. With vortex merging, a single frequency due to the merged vortex core is generated.

Zheng, Z. C. and Li, W.

"DEPENDENCE OF RADIATED SOUND FREQUENCY ON VORTEX CORE DYNAMICS IN MULTIPLE INTERACTIONS"

The Aeronautical Journal, Vol. 113, No. 1142, April 2009, pp. 233-242.

With both theoretical analysis and measurement data, it has been identified previously that there exists a robust sound emission from a pair of counter-rotating aircraft wake vortices at the frequency of unsteady vortex core rotation. In a vortex system with multiple vortices, the sound emission frequency can be subjected to change because of interactions among the vortices. The behavior of the influence, indicated by the ratio between the core size and the distance of the vortices and the underlying vortex dynamic mechanisms, is investigated in this study. A vortex particle method is used to simulate the vortex core dynamics in two-dimensional, inviscid, and incompressible flow. The flow field, in the form of vorticity, is employed as the source in the far-field acoustic calculation using a vortex sound formula. Cases of co-rotating vortices and a multiple-vortex system composed of two counter-rotating vortex pairs are studied for applications to aircraft wake vortex sound. The study shows, without vortex merging, individual frequencies can be clearly identified that are due each to core rotation (self-induction) and co-rotating motion of a vortex center around the other (mutual induction). The ratio of the core size and the distance between vortices does not seem to significantly influence the frequency of vortex core rotation. With vortex merging, a single frequency due to the merged vortex core is generated.

Zheng, Z. C. and Lim, S. H.

"VALIDATION AND OPERATION OF A WAKE VORTEX/SHEAR INTERACTION MODEL"

J. Aircraft, Vol. 37, No. 6, November-December 2000, pp. 1073-1078

A vortex method model developed previously for studying the mechanism in vortex/shear-layer interactions has been validated with large-eddy turbulence simulations and field measurement data. A shear-detection algorithm used to incorporate meteorological wind data is developed. Operational issues are also explored. The shear-thickness effects and the wind measurement resolution requirement and its sensitivity to the prediction algorithm are discussed. The objective of this work is to develop a computational method that is both accurate enough for the intended purpose and rapid enough to be of use in an operational setting at airports.

Zheng, Z. C. and Wei, Z.

"EFFECTS OF SURFACE ROUGHNESS AND PATTERNS ON A SURFACE-APPROACHING PAIR OF AIRCRAFT WAKE VORTICES"

AIAA Paper 2013-0364, January 2013, Grapevine, TX.

Surface roughness can have significant effects on the behavior of a pair of wake vortices approaching to the surface. In this paper, the effects of surface roughness are investigated using numerical simulation. Different types of surface roughness are simulated for both solid, stationary rough surfaces and moving wave surfaces. It has been shown from the results that because of more complicated secondary vortices generated near these rough surfaces than near a smooth surface, wake vortex trajectories and strengths can be significantly altered.

Zheng, Z. C. and Xu, Y.

"A VISUALIZED WAKE HAZARD ASSESSMENT"

AIAA Paper No. 2008-467, Reno, NV, January 2008

In this study, the rolling moment coefficient induced by wake vortices is considered an appropriate measure of wake vortex hazard on an aircraft encountering the wake generated by another aircraft. The rolling moment coefficient is calculated based on the strip theory treating the wake vortex velocity field as the downwash. The computation has been validated against wind tunnel experiment data. Numerical simulation results are then used to study the effects that influence the wake-vortex roll hazard, including vortex core size, follower aircraft size, atmospheric turbulence, and wake contortion due to sinusoidal-wave instability. These effects are displayed visually with two-dimensional and three-dimensional field contours to provide a dynamic and intuitive vortex hazard assessment.

Zheng, Z. C. and Xu, Y.

"BEHAVIORS OF VORTEX WAKE IN RANDOM ATMOSPHERIC TURBULENCE"

AIAA Paper 2009-0347, Jan. 2009, Orlando, FL

Atmospheric turbulence has significant influences on both the trajectories and the strengths of wake vortices. In this paper, a quasi-wavelet method is used to generate a random atmospheric turbulence

field based on the von Karman spectrum where atmospheric turbulence is represented by groups of random eddies. An inviscid wake vortex system in proximity to the ground is introduced in the generated turbulence background to study the effects of random turbulence on wake vortices. Wake trajectories with and without random turbulence are compared in the cases for non-decaying and decaying vortices.

Zheng, Z. C., Ash, R. L. and Greene, G. C.

"A STUDY OF THE INFLUENCE OF CROSS FLOW ON THE BEHAVIOR OF AIRCRAFT WAKE VORTICES NEAR THE GROUND"

Proceedings 19th ICAS Congress, Anaheim, CA, September 18-23, 1994, Vol. 2, pp. 1649-1659.

This paper studies the influence of cross wind on a vortex pair interacting with the ground. The study has been focused on exploring how various types of cross flow alter the trajectories and strengths of each vortex in different laminar ambient flows. The computation has employed the vorticity-streamfunction formulation of the Navier-Stokes equations. Then, the computational results are used to determine downwash velocities and induced rolling moment on hypothetical following aircraft, employing Prandtl's lifting line theory. This method provides alternative means to assess the wake vortex hazard.

Zheng, Z. C., Li, W., Wang, F. Y. and Wassaf, H.

"INFLUENCE OF VORTEX CORE ON WAKE VORTEX SOUND EMISSION"

Journal of Aircraft, Vol. 44, No. 4, July-August 2007, pp. 1369-1377

A consistent and persistent mechanism of sound emission from aircraft wake vortices has been identified. Both measurement data and theoretical results show that a dominant frequency of sound pressure matches the rotation frequency of a Kirchhoff vortex due to the self-induction inside the vortex core. Numerical simulations for more realistic wake vortex pairs with inviscid ground effects and shear flow are carried out using a vortex particle method. A far-field vortex sound formulation, based on asymptotic expansions, is developed and compared with formulae in the literature. The simulation results reveal that the frequency of the wake sound emission would remain essentially the same as the classical Kirchhoff vortex, even under the influences of an inviscid ground effect or a weak-shear cross wind. These results suggest that the mechanism identified should be robust.

Zheng, Z.-Q.

"INITIALIZATION AND COMPUTATION OF 3-D WAKE VORTICES"

Proceedings of the NASA First Wake Vortex Dynamic Spacing Workshop, NASA/CP-97-206233, edited by L. Credeur and R. Perry, NASA Langley Research Center, Hampton, VA, November 1997, pp. 202-211

The following topics are included in the presentation: (1) Axial velocity effects on 3-D Vortices; (2) Initial 3-D computational simulation with axial flow; and (3) The Zonal computational method. Conclusions include: (1) Initial axial velocity profiles influence the 3-D vortex decay behavior; (2) Axial velocity deviation can change the effects of vortex core growth on total circulation, axial vorticity, and maximum tangential velocity; (3) Computational results agree with the trend predicted in the analytical study; and (4) The zonal method can be utilized to extend far downstream 3-D simulation.

Zhenxing, G., Hongbin, G. and Hui, L.

"REAL-TIME SIMULATION OF LARGE AIRCRAFT FLYING THROUGH MICROBURST WIND FIELD"

Chinese Journal of Aeronautics, Vol. 22, 2009, pp. 459-466.

This article deals with real-time hi-fi simulation of large aircraft flying in turbulent wind in a simulator to study its takeoff and landing behavior in microburst wind shear. A parameterized three-dimensional (3D) microburst model is built up based on vortex ring and Rankine vortex principle. Complicated microburst wind fields are simulated by means of vortex ring declination and multi-vortex superposition. Based on the modeling data of Boeing B747-100, a dynamic model with wind shear effects considered is established and a general method to modify the aerodynamic model is proposed. A controller for longitudinal and lateral escapes is designed and verified in simulated microburst wind field. Results indicate that, with high extensibility, reasonability and effectiveness, the 3D microburst model with wind shear effects considered is fit to simulate real wind fields. Different escape schemes can be adopted to fly through a wind field from different locations. The model can be used for real-time flight simulation in a flight simulator.

Zhigulev, S. V., Kogan, M. N., Kuryachii, A. P., Litvinov, V. M. and Uspenskii, A. A.

"CONTROLLING THE NEAR VORTEX WAKE OF A SWEEPED HALF-WING BY MEANS OF MINI-FLAPS"

Fluid Dynamics, Vol. 43, No. 5, 2008, pp. 718-724.

The effect of mini-flaps on the flow pattern in the near vortex wake behind a model swept half-wing is investigated. The distributions of the time-average flow velocity were measured in a subsonic wind tunnel, in a section normal to the freestream velocity vector located at 3.8 wing half-spans from its trailing edge. When mini-flaps are mounted on both upper and lower wing surfaces, two vortices (tip and auxiliary) of the same sign are observable in the above-mentioned flow section; they are separated by an extended region of vorticity of the opposite sign. The model angle-of-attack effect on the intensities of the tip and auxiliary vortices is estimated.

Zhigulev, S. V., Kogan, M. N., Kuryachii, A. P., Litvinov, V. M. and Uspenskii, A. A.

"EFFECT OF MINI-FLAPS ON THE STRUCTURE OF THE NEAR WAKE BEHIND A MODEL HALF-WING"

Fluid Dynamics, Vol. 42, No. 2, 2007, pp. 212-220.

The effect of mini-flaps on the vortex structure of the near wake flow behind a model of a half-wing, rectangular in plan, is investigated. In a subsonic wind tunnel the time-average flow parameters are measured in several sections behind a model with flaps mounted on both upper and lower surfaces near the trailing edge. The wake flow parameters are compared with those for a model with no flaps. The considerable effect of the flaps on the flow structure in the viscous core of a tip vortex formed behind the model half-wing is established.

Zhong, B., Shaw, S. and Qin, N.

"BILU IMPLICIT MULTIBLOCK EULER/NAVIER-STOKES SIMULATION FOR ROTOR TIP VORTEX AND WAKE CONVECTION"

International Journal for Numerical Methods in Fluids, Vol. 55, 2007, pp. 509-536.

In this paper, A block incomplete lower-upper (BILU) decomposition method is incorporated with a multi-block three-dimensional Euler/Navier-Stokes solver for simulation of hovering rotor tip vortices and rotor wake convection. Results of both Euler and Navier-Stokes simulations are obtained and compared with experimental observations. The comparisons include surface pressure distributions and tip vortex trajectories. The comparisons suggest that resolution of the boundary layer is important for the accurate evaluation of the blade surface loading, but is less so for the correct prediction of the vortex trajectory. Numerical tests show that, using Courant-Friedrichs-Lewy (CFL) number of 10 or 30 with the developed BILU implicit scheme can be 6-7 times faster than an explicit scheme. The importance of solution acceleration schemes that increase the permitted time-step is illustrated by comparing the evolving wake structures at different stages of the calculation. In contrast to fixed wing simulations, the extent of the wake structures is shown to require resolution of large physical time. This observation explains the poor performance that is obtained when employing convergence acceleration strategies originally intended for solution of equilibrium problems, such as the multigrid methods.

Zhong, B., Shaw, S. T. and Qin, N.

"BILU IMPLICIT MULTIBLOCK EULER/NAVIER-STOKES SIMULATION FOR HELICOPTER ROTOR VORTICAL FLOW"

AIAA Paper No. 2005-0465, Reno, NV, January 2005

A Block Incomplete Lower-Upper (BILU) decomposition method is incorporated within a multi-block three dimensional Euler/Navier-Stokes solver for hovering rotor vortical flow simulation. The BILU method is used to solve the linear system arising at each step of the implicit time marching procedure. The inviscid flux is calculated using the Osher's approximate Riemann solver. Multi-block techniques are used to obtain a quality structured grid around the blade and in the near wake for better tip vortex and wake simulation. A modified MUSCL scheme is employed to alleviate the inaccuracy in the discretization. Numerical tests show that for fixed wing calculations the implicit scheme, using a CFL number of 30, can be 6-7 times faster compared to the time spent when using an explicit scheme. For rotating wing simulations numerical experiments demonstrate similar improvements. Compared to the

explicit scheme used for hovering rotor simulation, significant improvement in computational efficiency is achieved utilizing the BILU implicit scheme. The fidelity of the solutions is demonstrated by comparing results from Euler and Navier-Stokes solutions, including surface pressure distributions and vortex trajectories.

Zhong, J., Huang, T. S. and Adrian, R. J.

"EXTRACTING 3D VORTICES IN TURBULENT FLUID FLOW"

IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 20, No. 2, February 1998, pp. 193-199

This paper presents a computational framework to extract salient patterns, called vortex structures, from 3D turbulent fluid flows. These structures can be characterized as regions of dominating rotational motion in the velocity fields and intensity concentrations in the corresponding vorticity fields. A pointwise linear representation is employed to approximate the kinematics of the flow field, and the fluid motion is classified according to motion analysis or topological patterns. The regions of vortex structures are identified as those dominated by rotational motion or those of focus-type singularity. The 2D vortices, as a special case of 3D vortices, are detected by searching for regions of vorticity concentrations.

Zhou, A., Han, Y., Sun, D., Han, F., Zheng, J. and Zhang, N.

"HIGH EFFICIENCY ALL FIBER COHERENT LIDAR FOR WIND MEASUREMENT"

19th Coherent Laser Radar Conference (CLRC), Paper P16, June 2018, Okinawa, Japan.

Recently a high efficiency all-fiber coherent lidar system at 1.55-micron wavelength is developed to achieve real-time measurements of wind fields. The system employs 80-micro J-pulse energy at 10 kHz pulse repetition rate. In addition, the system consists of a fiber-based optical transceiver unit, a 2-axis scanner, and a multicore digital signal processor (DSP) for real-time signal processing. The lidar with compact and waterproof architecture can provide mobility, reliability, and ease of field deployment for wind measurements. And the high receiver efficiency provides for measurement range of wind up to 5km. Continuous wind profiles of the planetary boundary layer are presented to demonstrate the robustness and stability of the system.

Zhou, B., Wang, X., Wang, T. and Liu, J.

"INFLUENCE OF CROSSWIND SPEEDS ON AIRCRAFT WAKE VORTEX MOVEMENT"

ACTA Aeronautica et Astronautica Sinica, Vol. 30, No. 5, May 2009, pp. 773-779.

To enable the airdrome radar to detect and locate aircraft wake vortices in real time, a passive conservative model is proposed to simulate the wake vortices with reasonable assumptions about the flying environment. This model can depict reasonably well the movement evolution of water vapor and

other matter in wake vortices. This model takes into consideration the influence of crosswind speeds in the atmosphere on wake vortices, and is used to simulate the wake vortices in real time and find their distribution characteristics at different crosswind speeds and times. Analysis of the impact of crosswind speeds on aircraft wake vortices indicates that the most dangerous crosswind speed is between 1.0 and 3.0 m/s. This conclusion can be of theoretical value in the study of the impact of vortices on aircraft flying. [In Chinese.]

Zhou, H.

"ON THE MOTION OF SLENDER VORTEX FILAMENTS"

Physics of Fluids, Vol. 9, No. 4, April 1997, 970-981

Several approaches for slender vortex motion (the local induction equation, the Klein-Majda equation, and the Klein-Knio equation) are compared on a specific example of sideband instability of Kelvin waves on a vortex. Numerical experiments on this model problem indicate that all these equations yield qualitatively similar behavior, and this behavior is different from the behavior of a nonslender vortex with variable cross-section. It is found that the boundaries between stable, recurrent, and chaotic regimes in the parameter space of the model problem depend on the equation used. The boundaries of these domains in the parameter space for the Klein-Majda equation and for the Klein-Knio equation are closely related to the core size. When the core size is large enough, the Klein-Majda equation always exhibits stable solutions for our model problem. Various conclusions are drawn; in particular, the behavior of turbulent vortices cannot be captured by these approximations, and probably cannot be captured by any slender vortex model with constant vortex cross-section. Speculations about the differences between classical and superfluid hydrodynamics are also offered.

Zhou, L., Wan, Z., Sun, D.-J. and Wei, M.

"SOUND GENERATION BY DIFFERENT VORTEX INTERACTIONS IN MIXING LAYERS"

AIAA Paper No. 2012-1173, January 2012, Nashville, Tennessee.

To understand the correlation between far-field sound and near-field vortex dynamics, in this paper, we numerically investigate the sound generation from different types of vortex interaction (e.g. vortex pairing, vortex tearing, triple/quadruple-vortex merging). Direct Numerical Simulation (DNS) of the compressible Navier-Stokes equations is carefully conducted for an accurate description of far-field sound radiation. By choosing different phase delays between the fundamental frequency and its sub-harmonics, the vortex interaction changes from perfect pairing to tearing. The sound generated by vortex tearing is much quieter than the one from vortex pairing at the same excitation level. However, the directivity of sound radiations keeps almost the same. When different combinations of forcing frequencies are chosen, there are more complex triple and quadruple vortex mergings. The sound intensity of such cases is stronger than the one of either vortex pairing or vortex tearing. With more frequencies being involved, multi-directivity appears in triple/quadruple-vortex merging cases.

Zhou, Y. and Antonia, R. A.

"EFFECT OF INITIAL CONDITIONS ON VORTICES IN A TURBULENT NEAR WAKE"

AIAA Journal, Vol. 32, No. 6, June 1994, pp. 1207-1214.

The nature of turbulent vortices behind wake-generating bodies with similar dimensions depends on the initial conditions of porous or solid body wakes. Vortex strength, two-dimensional features, convection velocity topology and phase shift in the vortex shedding frequencies are different for the porous and solid body wakes. Solid body wake vortices contribute to Reynolds shear stress, and more to Reynolds normal stress than porous body wake vortices.

Zhou, Y., Zhang, H. J. and Whitelaw, J. H.

"WING-TIP VORTEX MEASUREMENT WITH PARTICLE IMAGE VELOCIMETRY"

AIAA Paper No. 2004-2433, Portland, OR, June-July 2004

Vortices shed from the tip of a rectangular half-span wing model (NACA 0012) have been investigated with flow visualization and a particle image velocimeter (PIV) at chord Reynolds number between $3.4 \times 10,000$ and $26.6 \times 10,000$, at distances from 0.2 to 5 chord lengths downstream and at angles of attack of 8 and 16 degrees. The tangential velocities, size and downstream evolution of the tip vortex were measured together with the growth in size and strength and of the formation length. The vortex core vorticity reached its maximum value at one and three chord lengths for angles of attack of 8 and 16 degrees. Perturbation of the tip vortex by blowing in the spanwise direction led to increased dispersion of the vortex and the otherwise stable vortex evolution or roll-up was disrupted. The extent to which the tip vortex was perturbed was sensitive to the velocity and position of the jet.

Zhu, R., Liu, J., Liu, Z. and Bao, F.

"EXPERIMENT ON A NEW CONCEPT WING LAYOUT WITH ALLEVIATED WAKE VORTEX"

Acta Aeronautica et Astronautica Sinica, Vol. 38, No. 4, April 2017, pp. 120250-1 to 120250-9.

Aircraft wake vortex will be produced by the wing tip to have a negative impact on flight safety, when a large aircraft applies flap wing to take-off and landing under a large angle of attack. Based on the Rayleigh-Ludwig instability, a new concept flap layout is developed by adding a set of specially designed flaps. Water channel experiments reveal that the new concept flap layout can significantly promote the wingtip vortex dissipation. The wingtip vortex which is affected by flap vortex with disparate parameter combinations performs differently with respect to movement characteristics and energy. The experiments also provide references to wake vortex control, when the requirement for flight mechanics design is satisfied. Building four-vortex system reasonably by taking advantage of high lift devices will have a significant effect on alleviating the intensity of aircraft wake, and improve the efficiency of aircraft take-off and landing at the airport. [In Chinese.]

Zhu, X., Liu, J., Zhang, X., Liu, Y., Zhu, X. and Chen, W.

"VALIDATION OF AIRBORNE 1.5 MICRON ALL-FIBER COHERENT LIDAR MEASUREMENT OF WIND PROFILES"

19th Coherent Laser Radar Conference (CLRC), Paper Th13, June 2018, Okinawa, Japan.

A high pulse energy 1.5-micron all-fiber coherent Doppler lidar airborne engineering prototype is developed for wind profiles measurement. The lidar system is very compact with 300 micro-J single pulse energy output and 100 mm telescope diameter, which could work in wide temperature range. Wind profiles are measured every 16 seconds with 60m range resolution. The airborne wind profiles measurement experiments-based UAV platform was successfully implemented. The airborne lidar measured wind speeds were compared with the ground-based coherent wind lidar and the GPS balloon, and good agreements were validated with wind speed standard error of less than 1 m/s from 1700 m to 3700 m.

Zikmund, P. and Mateju, J.

"DYNAMIC SOARING OF UNMANNED AERIAL VEHICLE WITHIN AIRLINER WAKE VORTEX IN CLIMB REGIME"

Journal of Aerospace Engineering, Vol. 231, No. 13, 2017, pp. 2479-2486.

The paper presents an analysis of an unmanned aerial vehicle gliding in an airliner wake vortex using the dynamic soaring principle. The goal of dynamic soaring is an improvement of flight performance of the unmanned aerial vehicle following an airliner. The paper extends previously published results of an airliner unmanned aerial vehicle climb regime flight formation analysis. Wake vortex model, the unmanned aerial vehicle basic parameters including drag polar and an airliner climb profile are taken from previous research. Dynamic soaring simulation within wake vortex is performed and evaluated. The presented results provide insight into energy balance and controllability of the unmanned aerial vehicle flying in an airliner wake vortex.

Zikmund, P. and Popela, R.

"AIRLINER-UAV FLIGHT FORMATION IN CLIMB REGIME"

International Journal of Aerospace and Mechanical Engineering, Vol. 9, No. 10, 2015, pp. 1786-1791.

Extreme formation is a theoretical concept of self-sustain flight when a big airliner is followed by a small UAV glider flying in the airliner wake vortex. The paper presents results of a climb analysis with the goal to lift the gliding UAV to airliners cruise altitude. Wake vortex models, the UAV drag polar and basic parameters and airliner's climb profile are introduced at first. Afterwards, flight performance of the UAV in a wake vortex is evaluated by analytical methods. Time history of optimal distance between an airliner and the UAV during a climb is determined. The results are encouraging. Therefore, available UAV drag margin for electricity generation is figured out for different vortex models.

Zilliac, G. G., Chow, J. S., Dacles-Mariani, J. and Bradshaw, P.

"TURBULENT STRUCTURE OF A WINGTIP VORTEX IN THE NEAR FIELD"

AIAA Paper No. 1993-3011, Orlando, FL, July 1993

The turbulent rollup of a vortex generated by a rectangular wing has been investigated. Extensive mean and turbulence measurements of the flowfield on a wingtip and in the near field have been completed. Velocity fluctuation measurements show that the near-field core is not laminar. A large axial velocity excess was found to exist in the core of the vortex. A momentum balance in the near-field of the wingtip showed that the magnitude of the core Reynolds-stress gradient terms is the same order as the largest terms in the governing equations. Navier-Stokes computations of the identical configuration, including wind tunnel walls and using measured inflow and outflow boundary conditions, reproduced many of the features of the experiment. Inherent limitations of the Baldwin-Barth turbulence model combined with limited grid resolution caused the computed vortex core to be more diffuse than desired. The momentum balance also demonstrated that the level of numerically generated false diffusion in the vortex core is relatively high.

Zioutis, C. K., Spyropoulos, A. I., Fragias, A. P., Margaritis, D. P. and Papanikas, D. G.

"INFLUENCE OF HELICOPTER ROTOR WAKE MODELING ON BLADE AIRLOAD PREDICTIONS"

International Journal of Engineering, Vol. 3, Issue 6, 2010, pp. 521-537.

In the present paper a computational investigation is made about the efficiency of recently developed mathematical models for specific aerodynamic phenomena of the complicated helicopter rotor flowfield. A developed computational procedure is used, based on a Lagrangian type, Vortex Element Method. The free vortical wake geometry and rotor airloads are computed. The efficiency of special models concerning vortex core structure, vorticity diffusion and vortex straining regarding rotor airloads prediction is tested. Investigations have also been performed to assess a realistic value for empirical factors included in vorticity diffusion models. The benefit of using multiple vortex line to simulate trailing wake vorticity behind blade span instead of isolated lines or vortex sheets, despite their computational cost, is demonstrated with the developed wake relaxation method. The computational results are compared with experimental data from wind tunnel tests, performed during joined European research programs.

Zioutis, X. K., Spyropoulos, A. I., Margaritis, D. P. and Papanikas, D. G.

"NUMERICAL INVESTIGATION OF BVI MODELING EFFECTS ON HELICOPTER ROTOR FREE WAKE SIMULATIONS"

24th International Congress of the Aeronautical Sciences, ICAS 2004, August 2004, Yokohama, Japan.

This paper presents the influences of numerical Blade Vortex Interactions (BVI) simulation on the computational results of rotor blade downwash distribution and airloading. This investigation is performed on the basis of a developed computational procedure utilizing Vortex Element Method for rotor free wake computations. By these means wake vortices are modeled by a series of discrete vortex elements and induced velocity on rotor disk is calculated for the distorted wake geometry, integrating Biot-Savart law in closed form over each one of them. Bound circulation variations and unsteady blade airloading because of the nonuniform induced downwash are computed utilizing a blade element like method. Wake roll up process, vortex core modeling, vorticity dissipation and elastic blade motion are some of the aerodynamic topics modeled with special care in the developed procedure. Using the computational flexibility of Vortex Element Method, BVI locations are captured and the phenomena are categorized as parallel, perpendicular, and oblique regarding their orientation relative to rotor blade. The corresponding intensity and locus for each category are calculated via a lifting surface methodology considering compressible blade flowfield. In addition, with the developed procedure the influence of each BVI phenomenon is isolated and its influence on blade downwash and airloads distribution is demonstrated. The computational results of BVIs location and strength distribution on rotor disk are compared with experimental data of blade airloading for several decent and level flight conditions. These data are derived from model-rotor wind tunnel tests, performed in the duration of joined European research programs.

Znamenskaya, I. P.

"SIZE REQUIREMENTS IMPOSED UPON THE PARTICLES USED FOR VISUALIZING AIRCRAFT VORTEX WAKES"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 146-150

Computational study has been carried out of the motion of small particles within a vortex aimed at working out the requirements to be imposed upon the size of particles used to visualize aircraft wakes. The motion of the particles of various size in Lamb's vortex was considered with accounting for the air turbulence effect on vortex sheet attenuation. The particles of 5-10 microns in diameter were obtained to be used for visualization purposes. [In Russian]

Zorea, C. and Rom, J.

"VORTEX ROLLUP OVER AND BEHIND WINGS RELATED TO NONLINEAR AERODYNAMIC CHARACTERISTICS"

J. Aircraft, Vol. 15, No. 4, April 1978, pp. 193-194

The present paper describes the investigation of the rolling up of vortices over and behind wings of rectangular and delta planforms. The present method can also be used to evaluate the loading of these wings. The method is based on the representation of the vortex distribution over the planform by a vortex lattice system incorporating in this calculation the influence of the vortices shed from these cells

into the flowfield. The evaluation of the diameter of the vortices far downstream of the wing, the spanwise position of the center of this vortex, and the appearance of the secondary vortices, which are some of the results obtained in this investigation, all are in reasonable agreement with available experimental results.

Zouaoui, Z., Szkatula, L. and Grant, R. J.

"COMPUTATIONAL ANALYSIS OF WAKE VORTICES GENERATED BY NOTCHED WINGS"

Journal of Aircraft, Vol. 44, No. 2, March-April 2007, pp. 487-500

The motivation behind the present investigations is the alleviation of vortex wake hazard. The present paper contains a 3-D computational analysis of the trailing wake vortices generated by notched (rectangular) wings, at a chord-based Reynolds number of $5.34 \times 10,000$. Various wing configurations were tested to determine the quantitative and qualitative effects of wing geometries on vortex dynamics. Two sets of computations were conducted up to 80 chord lengths downstream from the tip region. The first set used the conventional and notched-wing geometries for correlation of experimental and computed results. The second set of simulations concentrated on the development and testing of new wing designs. Wing geometries combined multiple tip (triangular/ogee) forms with the original notch design. The nature of vortices was classified in terms of their location, strength, and trajectories. Flow data were analyzed within these categories, at different crossflow planes behind the trailing edge. The first set of computational solutions demonstrated that the notched geometry significantly influenced the vortex location and strength of the wake system. The numerical results also confirmed that the tip and flap vortices generated by a notched wing remain distinct and unmerged, unlike those associated with the conventional wing. Finally, computed data demonstrated that the two-equation renormalization group turbulence model, combined with an appropriate treatment of the near-wall region can predict accurately steady and turbulent flows past wings. Very good agreement was obtained between the experimental and numerical results. Numerical simulations were performed for the second set of wing geometries to evaluate the effectiveness of wing modifications on the wake properties. Current results are promising: for all the cases considered, the wakes of the notched-triangular/ogee wings show maximum vorticity magnitudes that are substantially lower than those generated by the original notched wing. Numerical data clearly indicate that such geometrical combinations significantly reduce the wake strength and affect the merging process of the present vortex system.

Zsoldos, J. S. and Devenport, W. J.

"EXPERIMENTAL INVESTIGATION OF INTERACTING WING-TIP VORTEX PAIRS"

VPI-AOE-191, June 1992, Virginia Polytechnic Inst. and State Univ., Blacksburg, VA

The interaction of trailing vortex pairs shed from the tips of two rectangular wings have been studied through helium bubble flow visualizations and extensive hot wire velocity measurements made between 10 and 30 chord lengths downstream. The wings were placed tip to tip at equal and opposite

angles of attack, generating pairs of co-rotating and counter rotating vortices. Meaningful hot wire measurements could be made because the vortices were found to be insensitive to probe interference and experienced very small wandering motions. The co-rotating pairs were observed to rotate around each other and merge. Upstream of the merging location, the vortices have approximately elliptical cores. These are surrounded by the two wing wakes which join around the two cores.

Zubtsov, A. V.

"AN ASYMPTOTIC SOLUTION TO THE PROBLEM OF THE STRUCTURE OF A VORTEX PLAIT WITH CONSTANT CIRCULATION"

In: Investigation of Vortex Wake Evolution and Flight Safety - Collection of Papers, Trudy TsAGI, Vol. 2622, Publishing Dept. of TsAGI, Moscow, Russia, 1996, pp. 129-136

In the framework of an ideal fluid model, an asymptotic solution to the problem is constructed, which describes the constant-circulation vortex sheet structure in a domain far downstream from the site of its generation. [In Russian.]

Zubtsov, A. V.

"ON THE CIRCULATION 'DISSIPATION' IN THE VORTEX WAKE"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 121-124

The paper addresses the reason for unsteady circulation in the far vortex wake. Drop of circulation in the vortex wake with the distance from an aircraft is shown to be associated with the redistribution of vorticity vector flux in the three-dimensional flow region. Main physical factors influencing the variation of the vortex wake circulation are fluid viscosity, Reynolds stresses in the wake, and atmospheric turbulence.

Zudov, V. N.

"INTERACTION OF A STREAMWISE VORTEX WITH THE NORMAL SHOCK"

J. of Applied Mechanics and Technical Physics, Vol. 52, No. 5, 2011, pp. 734-743.

Interaction of a supersonic streamwise vortex with the normal shock is considered. Two interaction modes (weak and strong interaction) are identified. It is demonstrated numerically that strong interaction can lead to vortex breakdown.

Zudov, V. N. and Pimonov, E. A.

"INTERACTION OF A STREAMWISE VORTEX WITH AN OBLIQUE SHOCK WAVE"

J. Applied Mechanics and Technical Physics, Vol. 44, No. 4, 2003, pp. 461-470

Interaction of a supersonic streamwise vortex with an oblique shock wave is considered. A mathematical model of the streamwise vortex is constructed. Three interaction regimes (weak, moderate, and strong) are found. It is shown numerically that vortex breakdown is possible in the case of strong interaction. The influence of the governing parameters on the interaction type is studied. It is shown that the main effect on the interaction type is exerted by the streamwise velocity and angle of the wedge forming the shock wave. The effect of splitting of the primary vortex on the shock wave in the case of moderate and strong interaction regimes is found.

Zudov, V. N., Shevchenko, A. and Tretyakov, P. K.

"THE INTERACTION OF STREAMWISE VORTEX WITH A SHOCK WAVE"

20th International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF), Aug. 2003, pp. 258-267.

Experimental investigation of a longitudinal vortex/normal shock interaction is conducted at Mach numbers of 3, 4 and 6. The fields of total pressures in the core of a longitudinal vortex and its neighborhood are obtained. The optical visualization of flow structure in an interaction region is executed. The strongly unsteady character of interaction process is detected. The numerical modeling of the streamwise vortex interaction with the oblique and normal shock wave was solved using three-dimension unsteady Euler and Navier-Stokes equations. Results of an experimental study of the region of interaction of a plane shock wave arising in the flow around a wedge and an axisymmetric shock wave formed by counterflow injection with a jet wake formed by co-current injection of gases (H₂, air, Ar). Three interaction modes are distinguished, depending on the gas-jet parameters: strong interaction with a subsonic velocity in the wake, moderate interaction with the formation of a subsonic flow region bounded by the shock wave whose shape is close to conical, and neutral interaction where the dynamic pressure in the jet is sufficient to overcome the pressure difference on the shock wave.

Zuhal, L. and Gharib, M.

"NEAR FIELD DYNAMICS OF WING TIP VORTICES"

AIAA Paper No. 2001-2710, Anaheim, CA, June 2001.

An experimental investigation has been conducted to study the formation and near-field dynamics of a wing tip vortex. Stereoscopic PIV (SPIV), which allows instantaneous measurements of all three components of velocity within a planar slice, was used to measure velocity fields behind the wing. The present study has found that the wing sheds multiple vortices of opposite signs. Farther downstream, the vortices, with opposite sense of rotation, break up into smaller vortices which satellite around the tip vortex. At least one relatively strong satellite vortex appears in some of the instantaneous fields. The study found that the interaction of the tip vortex and satellite vortices give rise to the unsteady motion of the wing tip vortex.

Zuo, J.-J., Pan, W.-J., Liang, H.-J., Liang, Y.-A. and Deng, W.-X.

"ANALYSIS OF WAKE VORTEX SPACING REDUCTION TECHNOLOGY"

Proceedings of the International Conference on Service Robotics Technologies (ICSRT 2018), March 2018, Chengdu, China, pp. 57-61.

There are two main purposes for our research on wake vortex: one is to improve operation safety; the other is to reduce the wake spacing and ensure the runway capacity and operation efficiency under the premise of ensuring safety. By comparing and analyzing the technology of wake spacing reduction, we have studied aerial classification technology, synchronous offset approach technology, high glide slope approach technology, wake vortex warning system, aircraft wake vortex interval system and so on. Research shows that by proposing advanced concepts or improving the ATM program, namely the wake interval reduction technology, we can avoid the influence of the wake generated by the front aircraft, ensure the operation safety and increase the airport capacity by 3.7% - 25%. The key technology of the wake interval reduction technology is the wake vortex prediction model and the safety analysis of the wake encounter. However, the higher the accuracy of the model is, the more complex the computation is. The research on wake detection technology will be the future development direction.

Zurheide, F. and Schroder, W.

"NUMERICAL ANALYSIS OF WING VORTICES"

New Results in Numerical and Experimental Fluid Mechanics VI, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 96, 2008, pp. 17-25.

The temporal development of generic vortex systems based on Lamb-Oseen vortices is computed by large-eddy simulations. For a two-vortex system the growth of short-wave co-operative elliptical and long-wave Crow instabilities leads to a pronounced decay of its vorticity distribution. The four-vortex system possesses a smaller decay rate than the two-vortex system.

Zurheide, F. T., Huppertz, G., Fares, E., Meinke, M. and Schroder, W.

"INTERACTION OF WING-TIP VORTICES AND JETS IN THE EXTENDED WAKE"

Flow Modulation and Fluid-Structure Interaction, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 109, 2010, pp. 105-135.

The interaction of wing-tip vortices and jets in the extended wake is experimentally and numerically investigated. The measurements focus on the unsteady wake of a swept-wing half-model equipped with an engine jet and on the analysis of meandering vortex. The aircraft engine is modeled by a cold jet driven by pressurized air. To investigate the influence of the location of the engine jet on the vortex wake, it is mounted in two different positions under the wing model. The spatial development of a vortex wake behind a wing is simulated up to the extended near field. The measurements are used as

inflow distribution for a large-eddy simulation of the wake region. To better capture the motion of the wake vortices a method for hexahedral block structured adaptive mesh refinement with vertex-centered fluxes is introduced. The numerical simulations of the wake can predict trajectories and instabilities of the vortex core. The closer the engine is located near the root of the wing, the smaller is the deflection of the vortex and the fewer wave modes of the vortex are excited. The meandering motion of the vortex core is triggered by the engine jet.

Zurheide, F. T., Meinke, M. and Schroder, W.

"MEANDERING OF WING-TIP VORTICES INTERACTING WITH A COLD JET IN THE EXTENDED WAKE"

High Performance Computing on Vector Systems, Springer Berlin Heidelberg, 2009, pp. 223-242.

The spatial development of a vortex wake behind a half wing is simulated up to the extended near field. Results from wind tunnel measurements are used as inflow boundary conditions for an LES of the wake region. An aircraft engine is modeled in the experimental setup, where a cold jet is driven by pressurized air. The engine is mounted in two different positions under the wing model to investigate the influence of the location of the engine jet on the vortex wake. The numerical simulations of the wake can predict trajectories and instabilities of the vortex core. A position of the engine towards the root of the wing creates a smaller deflection of the vortex and excites fewer wave modes of the vortex.

Zurheide, F. T., Meinke, M. and Schroder, W.

"WING-TIP VORTEX / JET INTERACTION IN THE EXTENDED NEAR FIELD"

High Performance Computing in Science and Engineering, Part 5, 2009, pp. 269-283.

The vortex wake behind a half wing is spatially simulated up to the extended near field. Instabilities of the wing tip vortex are analyzed. Results from wind tunnel measurements are used as inflow boundary conditions for an LES of the wake region. An aircraft engine is modeled in the experimental setup, where the jet is driven by pressurized air. The engine was mounted in two different positions under the wing model to investigate the influence of the location of the engine jet on the vortex wake. The numerical simulations of the wake were able to predict trajectories and instabilities of the vortex core. A position of the engine towards the root of the wing created a smaller deflection of the vortex.

Zvonova, J. S.

"SIMULATION OF THE VORTEX WAKE EVOLUTION BEHIND THE AIRCRAFT IN THE FRAMEWORK OF A BOUNDARY-VALUE PROBLEM FOR THE EULER EQUATIONS"

In: Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity - Collection of Papers, Trudy TsAGI, Vol. 2641, Publishing Dept. of TsAGI, Moscow, Russia, 1999, pp. 176-182.

One of the most important factors limiting airport capacity is vortex wakes behind the aircraft during landing operations. Because of this, research into vortex wakes with the aim of their alleviation

becomes especially urgent. In the present work, the problem of the evolution of the far wake behind an aircraft and assessment of its lifespan is considered based on the Euler equations. The problem is solved without restrictions usually used in asymptotic theories. A method has been developed, that allows one to analyze the development of vortex filaments with the structure varying during their motion, which is impossible to do by asymptotic methods using the 'frozen' vortex structure hypothesis.

Zwack, P. and Tardif, R.

"USING THE COBEL COLUMN MODEL IN SUPPORT OF A WAKE VORTEX ADVISORY SYSTEM"

Proceedings of the International Wake Vortex Meeting, TP 13166, edited by H. Posluns, Transport Canada, Montreal, Ottawa, Canada, December 1997, pp. 125-126

Column (height-time) models represent an accurate and economical approach to the problem of analyzing the atmospheric structure and providing very short-range forecasts over specific sites. This presentation will focus on the COBEL column model for providing meteorological analysis and forecasts for airports. With funding from NASA and the FAA, COBEL is being adapted to provide accurate current and very short-term predictions of the atmosphere's vertical structure over the terminal area. The most recent development has been the implementation of a real-time version of COBEL during the Dallas-Fort Worth field measurement program. In this deployment, COBEL uses horizontal forcing (temperature and humidity advection, meso-scale vertical motions) and assimilates in-situ and remotely sensed measurements to provide an up-to-date vertical structure of the atmosphere.

Zwieback, E. L.

"TRAILING VORTICES OF JET TRANSPORT AIRCRAFT DURING TAKEOFF AND LANDING"

FAA-RD-64-3, January 1964, Douglas Aircraft, Long Beach, CA

The effect of ground plane and ambient winds on movement and strength decay was investigated. The results are compared with a modified potential flow theory. The position of the trailing vortices near the ground is extremely sensitive to low level ambient winds and vertical gradients of the wind. The measured positions of the trailing vortices indicate probable correlation with the potential flow theory with noted exceptions to the assumptions used. Measured vortex velocity decay rates are comparable to a modified theoretical free vortex viscous decay. Distinct vortex velocity fields were observed near the ground using a smoke generator technique for periods up to 65 seconds after aircraft passage. No differences in the trailing vortex system of two rolled-up vortices were observed for both the takeoff and landing configurations of the DC-8 aircraft.

Zwieback, E. L.

"TRAILING VORTICES OF JET TRANSPORT AIRCRAFT DURING TAKEOFF AND LANDING"

J. Aircraft, Vol. 1, No. 5, September-October 1964, pp. 308-310

A test program with a DC-8 determined that wing trailing vortex positions were extremely sensitive to low-level wind conditions, including vertical velocity gradients, and that the existing theories can predict the approximate behavior of the vortices near the ground. It is concluded from the test results that the location of trailing vortices near the ground cannot be accurately predicted based on routine wind data furnished by the control towers.